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HIGHWAY RESEARCH RECORD

Number 314

Costs and Benefits of Transportation Planning

12 Reports

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Subject Areas

15	Transportation Economics
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Foreword

This RECORD addresses itself to evaluating transportation investment criteria primarily from the user's point of view. Some of the topics covered in the papers are the value of time to the user of transportation facilities, the benefits accruing to transport users, costs of travel in terms of vehicle operating costs, congestion, the economics of system design, and regulation of vehicle weights. Methods for establishing highway needs and priorities for investment and techniques for economic evaluation of transportation investments are also discussed.

In recent years, it has become evident that transportation systems are a mixed blessing and have many social, economic, and environmental costs and penalties to the community, to society, and to the ecological balance in nature that may not be compensated for by the benefits of a new transportation system. The basic concept of benefit-cost analysis is being currently challenged. If the concept is good, the definition of the terms and factors to be included under costs and benefits are so enlarged that the traditional concepts and techniques are no longer adequate to establish criteria for the allocation of public resources for transportation or standards for defining needs or programs.

The papers included in this RECORD are illustrative of the paradox that highways and other modes of transportation now face. There are no clear procedures or techniques currently available to integrate community and national goals and values into the transportation planning process. At the same time, the user demands for transportation are increasing beyond current resources to add to the existing systems. Current transportation planning techniques have not yet adequately integrated community values, environmental quality, ecology, and intangible costs and benefits into the equations for determining the allocation of resources, the program priorities, or the location of transportation corridors. Until such time as adequate new procedures can be developed, current techniques will continue to have to be refined and amended and applied to situations where conflict between the community and the user is not a constraining factor.

Contents

The Value of Time for Commuting Motorists as a Function of Their Income Level and Amount of Time Saved

THOMAS C. THOMAS and GORDON I. THOMPSON, Stanford Research Institute

The value of travel time saved for commuting motorists is established as a function of the motorist's income level and amount of time saved. The results are based on data previously collected by Stanford Research Institute and used to estimate a constant value of time per minute saved of $2.82 per person per hour. The data were collected for commuters with a choice between a toll route and a free route. It was found that the value of time is higher for motorists with higher incomes, e.g., in the income range of $4,000-$15,000 per year, the value of time increases at the rate of approximately $0.20 per person per hour for each thousand dollars per year ($0.50 per hour) increase in income. For very small amounts of time saved, the value of time per minute is quite low. It increases with the amount of time saved and then decreases again. As an example, the equivalent hourly values for a motorist with a family income of $9,000 per year are as follows: the first minute saved is $0.79 per person per hour, the 14th minute saved is $3.72 per person per hour, and the 25th minute saved is $1.26 per person per hour.

The paper includes a table that provides the value of the amount of time saved as a function of the motorists' income level and the amount of time saved. These results are limited to commuter trips with time savings of not more than 30 minutes per one-way trip. The value of time is estimated from motorists' route choices as a function of the motorists' characteristics and the characteristics of the routes. A route choice model, based on the logit function, is used to predict the motorists' route choices between the alternative toll and free roads. The coefficients of the discriminant function in this model are then statistically estimated by finding their maximum likelihood estimates. From these estimates the indifference curve between toll per person and travel time saved is determined, the slope of which yields the desired value of time function.

•HIGHWAY PLANNERS, faced with heavy demands for improving highway facilities and constrained by limitations on funds available for construction, utilize the techniques of economic analysis to assist them in making better decisions on the expenditure of these funds. Economic analysis provides information for the evaluation of highway improvement projects, the development of priorities for the construction of highway projects within a political jurisdiction, and the assessment of alternative features of engineering design and layout for projects.

Economic analysis considers the effects of highway improvements on the highway agency in terms of increased costs for construction and maintenance of improved highways, on the highway users in terms of reduced accidents and congestion and savings in travel time and vehicle operating costs, and on the nonusers in terms of changed land values and atmospheric pollution. To include these effects in an economic analysis, all benefits must be stated in dollar values.

Paper sponsored by Committee on Highway Engineering Economy and presented at the 49th Annual Meeting.

The reduction in motorists' travel times is often a major benefit of proposed highway improvement projects; lesser benefits result from the reduction in motor vehicle operating and accident costs. Consequently, converting time saved from hours to dollars is critically important in analyses of alternative highway locations and designs. The factor used to make this conversion is called the value of time.

Even though value-of-time factors have been used for years in highway economic analysis, relatively little reliance could be placed on the accuracy of these values. The commonly accepted value of $0.86 per person per hour used in the 1965 AASHO Handbook represents only the opinion at that time on a logical and practical value. Research into establishing the value of time has increased in recent years, but until 1967 the efforts failed to determine values that could be used with confidence in specific situations.

In 1967 two empirical studies of the value of time for commuters appeared. One study, a doctoral dissertation (1), used data on commuter choices between the Skokie-Swift rail transit south of Chicago and automobile transportation to estimate the value of time as between $2.50 and $2.70 per person per hour. The Stanford Research Institute (SRI) report (3) sampled commuters' choices between a toll road and free road in their home-to-work and work-to-home trips from eight areas of the country and estimated a constant value of time as $2.82 per person per hour.

This paper presents the results of further analyses of the SRI data. The main objective of the paper is to estimate a value of time that is a function of other variables such as income or the amount of time saved. This paper is written so that knowledge of previous SRI studies is not necessary. However, other information (2, 3) is recommended to the reader who wishes a deeper understanding of the theoretical, methodological, and empirical bases for estimating a value of travel time saved.

APPROACH TO PROBLEM

The value of time saved is conceptualized in terms of a commuting motorist's indifference curve for a choice between two alternative routes. In microeconomic terminology, the value of time is the slope of the motorists' indifference curve for alternative trip cost and trip time saved; i.e., it is the rate at which the motorist is willing to trade more money for less travel time. In the real-life situation in which many motorists each face a different route choice, the money versus time-saved trade-off cannot be directly observed. Rather it must be inferred from the relationships that emerge when route choices of motorists are estimated from data on alternative trip costs and time saved and from other data on route and motorist characteristics that affect route choice. The coefficients of the route and motorist variables in the route choice estimator specify the relative importance of each variable to the motorist's choice and therefore can be used to calculate the trade-off between cost and time saved, i.e., the value of time.

In the previous SRI study (3), data were collected on commuters and their routes in situations where the commuter had a choice between saving travel time on a toll route and saving money (the toll) on a free route. Eight toll-route and free-route pairs in different areas of the country were studied.

Two types of on-route characteristics were collected. The first type, referred to as measured data, was recorded by a test vehicle that drove the routes, "floating" with the average traffic flow. The vehicle was equipped with a fifth wheel and associated electronics that measured and recorded the car's velocity every second. The second type, referred to as reported data, came from interviews with each motorist who was identified in the study as having a choice between the toll road and the free road. The interviewers collected information on the motorist's perceptions of the alternative routes, e.g., travel time, safety, and scenic beauty. Both measured and reported data provided estimates of such quantities as travel time and distance. The measured data yielded profiles of physical characteristics not obtainable by interview, such as number and size of speed change units on each route, whereas the reported data provided psychological measurements of their perceptions of safety, comfort, and "safe" speeds. The interviews were the sole source of the motorist data. Measured and reported data for route characteristics were combined separately with the motorist data to determine

two different estimates of motorist route choices between the toll road and the free road.

The mathematical formulation of the route-choice model treated each driver as a separate data point with a binary choice, i.e., toll road or free road. The analysis estimated the route choice by using a logit function that can be expressed in the following form:

$$p(x) = \frac{e^{f(x)}}{1 + e^{f(x)}}$$

where

$p(x)$ = the probability of taking the free road,
e = the base of natural logarithms, and
$f(x)$ = a function of the characteristics of the route and motorist.

When a motorist chose the toll road, the observed $p(x)$ was assigned a value of zero; when he chose the free road, the observed $p(x)$ was assigned a value of one. The $f(x)$ was restricted to a linear function of the characteristics of the route and motorist, i.e.,

$$f(x) = a_0 + a_1x_1 + a_2x_2 + \dots + a_nx_n$$

where the a_i units are coefficients to be estimated, and the x_i units are characteristics of the motorist, such as income or sex, or of the routes, such as travel time, toll cost, or number of speed change units.

The $p(x)$ can be interpreted in two ways: (a) as a probability estimate of the individual motorist's choice or (b) as the percentage split of a group of motorists all with the same characteristics (the same values) of the independent variables. When the estimated $p(x)$ is equal to or greater than 0.5, an individual motorist would be assumed to use the free road; when the estimated $p(x)$ is less than 0.5, he would be assumed to use the toll road. For a group of motorists, the $p(x)$ can be interpreted as the percentage split between routes.

Once the parameters of the route-choice model have been estimated, it is a simple calculation to estimate the value of travel time saved from the function $f(x)$. The motorist is estimated to be indifferent to the choice of alternative routes when $p(x)$ equals 0.50. For $p(x) = 1/2$, $f(x) = 0$, or

$$0 = a_0 + a_1x_1 + a_2x_2 + \dots + a_nx_n$$

This equation can be solved for the toll charge (one of the x_i units) that the motorist will pay in terms of his psychological characteristics and the characteristics of the alternative routes. The derivative of the toll charge with respect to travel time saved is inferred to be the traveler's value of time, i.e., the trading ratio between toll and time saved at the indifference point.

In the case of the $f(x)$ used in the previous study (3), in which both toll and the difference in travel time appeared only to the first power, the value of time is simply the ratio of the coefficients of the difference in travel times and toll estimated in the route choice model. That is,

$$\text{value of travel time saved} = \frac{\text{coefficient of travel time saved}}{\text{coefficient of toll costs}}$$

The "best" model using the measured route data estimated a value of commuter travel time saved of \$1.82 per hour with a standard error of \$0.40 per hour. The value of time based on reported route data was considerably higher at \$3.82 per hour with a standard error of \$0.85 per hour. These values of time are for the 50th percentile or median motorist.

The definition of the value of time in terms of the motorist's indifference curve makes his perceptions of route characteristics at the time of his route-choice decision the correct variables (2) to place in the model. In general, neither the measured nor the reported data fully meet the requirements for perceived data (see Appendix for further discussion). However, in the previous report (3) it was shown that the value of time based on measured route characteristics would be less than the motorist's true value of time, whereas that based on the reported route characteristics would be greater than the motorist's true value of time. Therefore, the average of these two values, \$2.82 per hour, was selected in the previous study as a reasonable approximation of the true value of travel time saved for the mean commuter. The \$2.82 per person per hour is a constant value of time, i.e., it is independent of income level, amount of time saved, and other route and motorist characteristics.

THE REANALYSIS—AN OVERVIEW

The main objective of this study is to estimate a value of time that is not a constant, but rather a value that is a statistically significant function of other variables such as income or the amount of time saved.

Two main obstacles stood in the path of this objective. The first, and less formidable, was the divergence of the constant value of time based on measured data from the constant value of time based on reported data. This divergence raised questions about the validity of the data and analysis approach. The divergence problem was resolved mainly through "corrections" to the time saved as measured by the test vehicle. The result was a sizable increase in the value of time based on the measured data. By one approach, that of adjustment, the gap between the measured and reported value of time was cut in half. The other approach, filtering, resulted in the two estimates becoming approximately equal. The details of the analysis are given in the Appendix. Both approaches increased the confidence in the use of the reported route data to estimate the value of time rather than the use of the measured route data, given the limitations faced in collecting measured data in different geographic areas of the country.

The second, and more formidable, obstacle was the problem of the constant value of time estimated in the previous report. At the very least, the "true" value of time can be expected to vary with the motorists' income level and the amount of time saved. The specific relationships are as follows:

1. The hypothesized relationship between the value of time and income is simply the higher the motorist's income, the higher his expected value of time if trip characteristics and other motorist characteristics are held constant. In the original formulations of the logit model, in which the variables of time saved, income level, and toll appear only to the first power in f(x), the value of time is functionally independent of income. However, the toll charge that the motorist is willing to pay to save travel time is a function of income. A contradiction thus arises when the value of time is estimated to be independent of income while the toll a motorist is willing to pay to save time is a function of income. This conflict must be resolved.

2. The hypothesized relationship between the value of time and the amount of time saved for a particular type of trip results in an S-shaped benefits curve in the total benefits (i.e., toll charge the motorist is willing to pay) versus time-saved plane as shown in Figure 1. For very small amounts of time saved, empirical evidence indicates that motorists are insensitive to reductions in trip time, while economic theory suggests an eventual diminishing marginal utility of time saved as the amount of time saved continues to increase (2). This relationship yields a value of time that is a function of the time saved. The marginal value of time is the slope of the total benefits versus the time-saved relationship, i.e.,

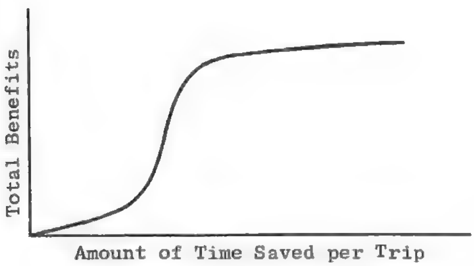

Figure 1. Total benefits function.

$$V_T = \frac{d(T.B.)}{d\Delta t}$$

where

V_T = marginal value of time;
T.B. = the total benefits function, i.e., willingness to pay this level of toll; and
Δt = the time saved.

The linear f(x) that provides the constant value of time is viewed as an approximation to the hypothesized curve in the 5- to 20-minute range of time saved, where nearly all the relevant data points are located.

Figure 2 shows the fit of a constant value of time to the hypothesized curve. This linear approximation has the undesirable characteristic of showing negative willingness to pay a toll (i.e., total benefits) for small positive time saved; that is, it intersects the time-saved axis at some positive amount of time saved.

The linear function provides a reasonable approximation for total benefits versus the amount of time saved per trip. However, the definition of the value of time as the slope of the linear approximation can result in a large estimate of the benefits of time savings even when the total benefits or willingness to pay a toll is estimated to be zero. For example, if the value of time is 5 cents per minute, then a 4-minute time savings is valued at 20 cents, but total benefits would be estimated to be zero (or negative).

The previous reports (2, 3) discussed the possible errors in estimating benefits that could result from using the constant value of time. However, it was not possible within the limitations of that contract to statistically estimate a variable value of time, i.e., one that varied as a function of income level and amount of time saved; this limitation needed to be corrected.

This report describes the results that were obtained in the present contract by using two techniques to estimate a variable value of time: (a) using higher order terms in f(x) in the logit model, and (b) making piecewise linear estimates of the value of time.

HIGHER ORDER TERMS IN f(x)

Several polynomial forms for the discriminant functions were considered that involved first-, second-, and third-order terms in the three variables where c = toll per person, I = income level of the motorist, and Δt = travel time saved. The higher order terms in the discriminant function can potentially improve the "fit" of the estimated total benefits function to the hypothesized curvilinear model. Preliminary analyses reduced the number of higher order terms worthy of further study to six that contained the variables for income level and travel time saved.

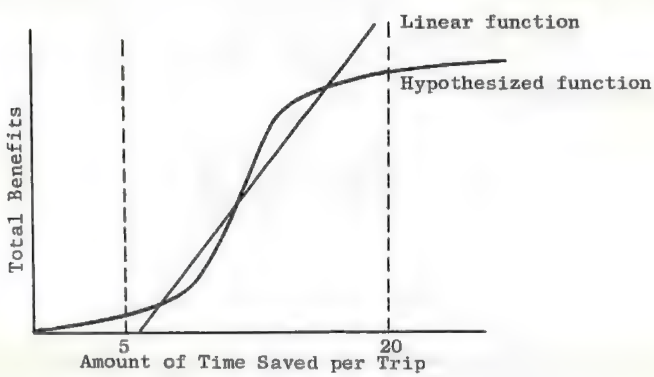

Figure 2. A linearly estimated total benefits function.

An example of an estimated f(x) with higher order terms in I and Δt is

$$f(x) = a_0 + a_c c + a_I I + a_{\Delta t}\Delta t + a_{I\Delta t} I\Delta t + a_{\Delta t^2}\Delta t^2$$

The total benefits of the toll road, defined as the maximum toll charge the average motorist is willing to pay, can be found by setting $p(x) = 0.5$. Then $f(x) = 0$, and the total benefits can be solved for as follows:

$$\text{T.B.} = c = \frac{-1}{a_c}\left(a_0 + a_I \cdot I + a_{\Delta t} \cdot \Delta t + a_{I\Delta t} \cdot I \cdot \Delta t + a_{\Delta t^2} \cdot \Delta t^2\right)$$

The value of time is

$$V_T = \frac{d(\text{T.B.})}{d\Delta t}$$

$$= -\left(\frac{a_{\Delta t}}{a_c} + \frac{a_{I\Delta t}}{a_c} \cdot I + \frac{2a_{\Delta t^2}}{a_c} \cdot \Delta t\right)$$

or

$$V_T = \beta_0 + \beta_1 I + \beta_2 \Delta t$$

where β_i units are the coefficients determined by differentiating the total benefits function.

The potential importance of the higher order terms can be seen in this last equation; the value of time would be a function of the income level of the motorist (I) and the exact increment of time saved (Δt). The result is that the statement "the value of time is \$3.30 per hour" is no longer valid for all income levels and amounts of time saved.

In general, the results of the use of the higher order terms were quite disappointing for the following reasons:

1. Many of the coefficients were not significant at the 95 percent confidence level.
2. In several instances, the maximum likelihood estimate had a sign opposite to that predicted theoretically.
3. The improved models had no greater success in predicting route choice decisions than the linear models.
4. Differences in the value of time and in the total benefits made by the higher order terms were quite small for most of the models over the range of time savings covered by the majority of the data, i.e., 5 to 20 minutes.

The only higher order f(x) with 95 percent confidence level for all coefficients was

$$f(x) = a_0 + a_c \cdot c + (a_{\Delta t} + a_{I\Delta t} \cdot I) \cdot \Delta t$$

The value of time for this f(x) is

$$V_T = -\left(\frac{a_{\Delta t}}{a_c} + \frac{a_{I\Delta t}}{a_c} \cdot I\right)$$

or

$$V_T = \beta_0 + \beta_I \cdot I$$

The value of time is then estimated as a linear function of the income level of the motorist. The coefficients β_0 and β_I were estimated by using the adjusted reported and adjusted measured data. They are given in Table 1.

TABLE 1

INCOME-DEPENDENT VALUE OF TIME ESTIMATES

Data Set	Sample Size	Value of Time (dollars per hour)	Value of 1 Hour of Time Saved		
			I = 2	I = 4	I = 6
Reported-adjusted	807	1.803 + 0.461·I (0.628) (0.174)	\$2.73	\$3.64	\$4.57
Measured-adjusted	510	1.850 + 0.181·I (0.735) (0.127)	\$2.31	\$2.57	\$2.94

Note: The figures in parentheses are the standard errors of the estimates.

Income (I) level 1 is under \$4,000 per year;
2 is \$4,000-\$5,999 per year;
3 is \$6,000-\$7,999 per year;
4 is \$8,000-\$9,999 per year;
5 is \$10,000-\$11,999 per year;
6 is \$12,000-\$14,999 per year;
7 is \$15,000-\$20,000 per year; and
8 is over \$20,000 per year.

The relative magnitudes of the constant term and the coefficient of income level indicate a major dependence of the value of time on the income level of the motorist, particularly for the reported-adjusted data. The confidence in this dependence is reflected in the small standard errors; all coefficient estimates are significant at the 95 percent confidence level. An average of the two estimates based on adjusted data gives a $V_T = 1.83 + 0.32 \cdot I$.

Therefore, using higher order terms in f(x), it has been possible to establish the value of time as a function of income. However, the dependence of the value of time on the amount of time saved could not be estimated at a statistically significant level by using higher order terms in f(x).

PIECEWISE LINEAR ESTIMATES

A second approach to estimating a value of time that is a function of the amount of time saved was to make estimates using subsets of the data limited to different ranges of time saved. The result is that different values of time can be estimated for each range of time saved, e.g., 0 to 5 minutes, 5 to 15 minutes, and more than 15 minutes, which provides a value of time dependent on the (range of) time saved. In making these estimates the f(x) that gave a value of time dependent on income level was used, i.e.,

$$f(x) = a_0 + a_c \cdot c + (a_{\Delta t} + a_{\Delta t} \cdot I)\Delta t$$

Considerable effort was expended in testing alternative definitions for the data subsets. The boundaries and numbers of data subsets were varied; both overlapping and nonoverlapping subsets were tried. Variations in f(x) using Δt^2 or Δt^3 were also tested to see if a better fit could be obtained for a limited range of time saved.

Many of the estimates, particularly for the more constrained ranges of Δt, did not yield good standard errors. However, when all the estimates were plotted together they generally fell on top of each other. As a result, an overall picture of total benefits versus time saved was built up in which we have considerable confidence.

The resultant graph of benefits versus time saved for adjusted reported data is shown in Figure 3. Less desirable statistical properties occurred for the measured adjusted data and filtered data.

Two of the more important estimates on which Figure 3 is based are

$$\text{5 to 15 minutes:}\quad \text{T.B.} = \underset{(15.35)}{-40.86} + \underset{(1.12)}{3.06\Delta t} + \underset{(0.298)}{0.811 I \cdot \Delta t}$$

$$\text{15 or more minutes:}\quad \text{T.B.} = \underset{(20.60)}{8.25} + \underset{(1.41)}{0.16\Delta t} + \underset{(0.24)}{0.47 I \cdot \Delta t}$$

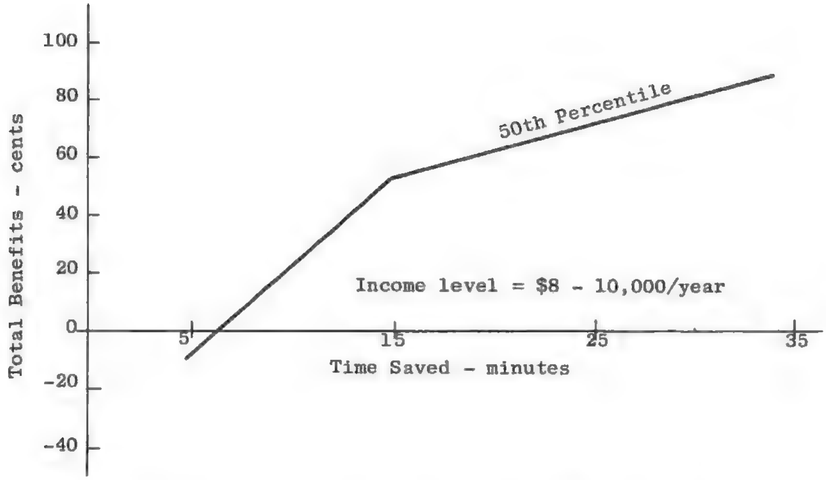

Figure 3. Estimated 50th percentile total benefits function.

In the second estimate, the $I \cdot \Delta t$ term predominates over the Δt term (which is not significantly different from zero) to dictate the slope of the value of time for a time saving of more than 15 minutes. The intercept is not statistically significant and was adjusted slightly in fitting the curves together. All coefficients in the first equation are statistically significant. However, as previously stated, these are only two of a number of different estimates that give approximately the same results.

Therefore, when using estimators that are piecewise linear in the amount of time saved (but a function of income level), the marginal value of time is found to decrease for time saved of greater than 15 minutes. However, the nature of the data precluded statistical estimates of the value for the 0- to 5- minute range. For time saved of less than 5 minutes and more than 0 minutes there are very few reported data points because of the motorist's tendency to report in multiples of 5 minutes. The measured data also have problems in this range of time saved because a small perceptual error by the driver can turn a positive time saved into a negative time saved. Therefore it is hard to focus the empirical analysis on a small amount of time saved. Another approach had to be taken.

One property of the route choice estimators was that, in the final form of the model, the only route characteristic used was the time difference between the two routes. This was a result of extensive analysis, not an assumption of the analysis. Route choice models were built using as variables the differences in distance, several alternative measures of differences in amount of speed changes on the routes, measures of differences in waiting times, differences in perceived safety, differences in perceived driving pleasure, and other variables. The estimators using these additional route-characteristic variables all suffered from some combination of (a) the wrong sign on their coefficients, (b) large standard errors of estimate, and (c) no improvement in route choice prediction. Thus, only the time difference and toll plus motorist characteristics are included in the final models. The time difference between routes was found to be the only route variable for which motorists perceived a benefit and would be willing to pay.

The empirical evidence from the body of data under analysis gives scant weight to suppositions about "other reasons" for taking the toll or free road other than the toll and time difference. Thus, in the case where the same vehicle would be used on either route, it appears appropriate to impose the boundary condition that the relationship between the total benefits of taking the toll road and the amount of time saved must be non-negative and go to zero as the time difference goes to zero. This is a crucial assumption. However, a 1- or 2-cent positive or negative vertical intercept would not

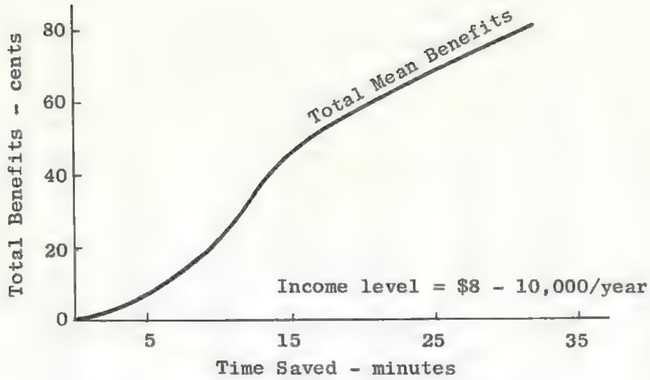

Figure 4. Total mean benefits function.

change the results appreciably. By contrast, the intercept of the linear estimator implied the requirement of a negative toll, i.e., a payment to the motorist, of some 40 cents for the average motorist (earning $8,000 to $10,000 per year) to take the toll road when there was no time difference.

The other reasonable (and less important) assumptions are that (a) the relationship is continuous and smoothly joins the empirically estimated curves, and (b) the motorist tends to be insensitive to time differences of less than a minute so that the relationship approaches the origin along the time-saved axis. The application of these assumptions results in a constraint on the total benefits curve. When a benefit line (relationship) reaches the time-saved axis (i.e., zero total benefits), it must be constrained from going lower. Thus, in Figure 3 the benefits relationship for the 50th percentile motorist (i.e., for $p(x) = 0.5$) would be altered so that after it reaches zero benefits for a time saving of 6.5 minutes it would go along the time-saved axis and not cross it. However, this does not mean that all motorists at this income level have ceased to be willing to pay for a time saving of 6.5 minutes. The 25th percentile motorist has zero benefits starting at 9.7 minutes, whereas the 75th percentile motorist has zero benefits starting at 3.2 minutes.

Therefore, constraining benefits to be greater than or equal to zero results in the distribution of motorists' benefits no longer being symmetrical about the 50th percentile motorist for small time saved. The mean is no longer equal to the median. The mean benefits are now above the 50th percentile benefits and thus the mean-benefits line departs from the 50th percentile line and must be recalculated as the distribution changes. The total (mean) benefits versus the time-saved graph that was calculated is shown in Figure 4.

A similar but higher curve is estimated for income levels above $10,000, and a similarly shaped but lower curve is estimated for income levels below $8,000. The value of time is now estimated as a function of both income level and amount of time saved. The empirical form of the relationship agrees with the hypothesized form.

Table 2 gives total values of time for from 1 to 30 minutes time saved per commuter trip for each of the eight basic income levels studied. These are not incremental values for the specific minute saved, but reflect the total value for the full time savings indicated.

For example, consider a commuter whose income places him in income level 4. He will value 4 minutes of time saved at 5.2 cents, 8 minutes of time saved at 15.0 cents, and 16 minutes of time saved at 51.4 cents. Note that the 16-minute time saving is not valued at twice the 8-minute time saving, nor a 4-minute time saving at half the value of an 8-minute time saving. The marginal value of time for 1 minute of time saved first increases as the time saved increases up to approximately 14 minutes, and then decreases thereafter.

To aid the reader in seeing the changes in the value of time, Table 3 has been calculated from Table 2 to show the equivalent hourly values of time saved, e.g., the value

TABLE 2

TOTAL VALUE OF TIME SAVED IN DOLLARS

Time Saved in Minutes	Income Level of Motorist[a]							
	1	2	3	4	5	6	7	8
1.00	0.007	0.009	0.011	0.013	0.016	0.019	0.023	0.027
2.00	0.014	0.018	0.022	0.026	0.032	0.038	0.045	0.054
3.00	0.022	0.027	0.032	0.039	0.048	0.057	0.068	0.081
4.00	0.029	0.035	0.043	0.052	0.063	0.076	0.091	0.108
5.00	0.036	0.044	0.054	0.066	0.079	0.095	0.114	0.135
6.00	0.044	0.056	0.070	0.088	0.109	0.134	0.162	0.194
7.00	0.053	0.070	0.090	0.116	0.146	0.182	0.222	0.267
8.00	0.064	0.086	0.115	0.150	0.192	0.240	0.293	0.351
9.00	0.077	0.106	0.144	0.190	0.245	0.306	0.372	0.442
10.00	0.091	0.130	0.178	0.237	0.304	0.378	0.456	0.537
11.00	0.108	0.156	0.217	0.289	0.369	0.454	0.543	0.633
12.00	0.128	0.187	0.260	0.344	0.437	0.533	0.632	0.731
13.00	0.149	0.220	0.306	0.403	0.507	0.613	0.721	0.828
14.00	0.173	0.257	0.356	0.465	0.579	0.694	0.810	0.925
15.00	0.180	0.271	0.373	0.493	0.612	0.731	0.849	0.967
16.00	0.188	0.283	0.389	0.514	0.637	0.761	0.884	1.007
17.00	0.196	0.295	0.405	0.534	0.662	0.790	0.918	1.046
18.00	0.203	0.307	0.421	0.555	0.688	0.820	0.953	1.085
19.00	0.212	0.319	0.437	0.575	0.713	0.850	0.987	1.124
20.00	0.220	0.331	0.453	0.596	0.738	0.880	1.022	1.163
21.00	0.228	0.345	0.468	0.616	0.763	0.910	1.056	1.202
22.00	0.236	0.357	0.484	0.637	0.788	0.939	1.090	1.242
23.00	0.245	0.369	0.500	0.657	0.813	0.969	1.125	1.281
24.00	0.253	0.381	0.516	0.677	0.838	0.999	1.159	1.320
25.00	0.262	0.393	0.532	0.698	0.863	1.029	1.194	1.359
26.00	0.270	0.405	0.548	0.718	0.888	1.058	1.228	1.398
27.00	0.279	0.419	0.563	0.739	0.914	1.088	1.263	1.437
28.00	0.287	0.431	0.579	0.759	0.939	1.118	1.297	1.477
29.00	0.296	0.443	0.595	0.780	0.964	1.148	1.332	1.516
30.00	0.304	0.455	0.611	0.800	0.989	1.178	1.366	1.555

[a]Income levels as given in Table 1.

TABLE 3

HOURLY EQUIVALENTS OF THE TOTAL VALUE OF TIME SAVED IN DOLLARS

Time Saved in Minutes	Income Level of Motorist[a]							
	1	2	3	4	5	6	7	8
1.00	0.43	0.53	0.65	0.79	0.95	1.14	1.36	1.62
2.00	0.43	0.53	0.65	0.79	0.95	1.14	1.36	1.62
3.00	0.43	0.53	0.65	0.79	0.95	1.14	1.36	1.62
4.00	0.43	0.53	0.65	0.79	0.95	1.14	1.36	1.62
5.00	0.43	0.53	0.65	0.79	0.95	1.14	1.36	1.62
6.00	0.44	0.56	0.70	0.88	1.09	1.34	1.62	1.94
7.00	0.45	0.60	0.77	0.99	1.25	1.56	1.91	2.29
8.00	0.48	0.65	0.86	1.12	1.44	1.80	2.20	2.63
9.00	0.51	0.71	0.96	1.27	1.63	2.04	2.48	2.95
10.00	0.55	0.78	1.07	1.42	1.82	2.27	2.74	3.22
11.00	0.59	0.85	1.18	1.57	2.01	2.48	2.96	3.46
12.00	0.64	0.93	1.30	1.72	2.18	2.67	3.16	3.65
13.00	0.69	1.02	1.41	1.86	2.34	2.83	3.33	3.82
14.00	0.74	1.10	1.53	1.99	2.48	2.97	3.47	3.96
15.00	0.72	1.08	1.49	1.97	2.45	2.92	3.40	3.87
16.00	0.70	1.06	1.46	1.93	2.39	2.85	3.31	3.77
17.00	0.69	1.04	1.43	1.89	2.34	2.79	3.24	3.69
18.00	0.68	1.02	1.40	1.85	2.29	2.73	3.18	3.62
19.00	0.67	1.01	1.38	1.82	2.25	2.68	3.12	3.55
20.00	0.66	1.00	1.36	1.79	2.21	2.64	3.06	3.49
21.00	0.65	0.98	1.34	1.76	2.18	2.60	3.02	3.44
22.00	0.64	0.97	1.32	1.74	2.15	2.56	2.97	3.39
23.00	0.64	0.96	1.30	1.71	2.12	2.53	2.93	3.34
24.00	0.63	0.95	1.29	1.69	2.10	2.50	2.90	3.30
25.00	0.63	0.94	1.28	1.67	2.07	2.47	2.87	3.26
26.00	0.62	0.94	1.26	1.66	2.05	2.44	2.83	3.23
27.00	0.62	0.93	1.25	1.64	2.03	2.42	2.81	3.19
28.00	0.61	0.92	1.24	1.63	2.01	2.40	2.78	3.16
29.00	0.61	0.92	1.23	1.61	1.99	2.37	2.76	3.14
30.00	0.61	0.91	1.22	1.60	1.98	2.36	2.73	3.11

[a]Income levels as given in Table 1.

of six 10-minute periods of time saved or twelve 5-minute periods of time saved. Note that, although the equivalent hourly value of an 8-minute period of time saved at income level 4 is $1.12, the equivalent hourly value of the 8th minute itself, i.e., $d(T.B.)/d\Delta t$ at 8 minutes, is approximately $2.04 (the value in Table 2 of 8 minutes minus the value of 7 minutes times 60).

CONCLUSIONS

The most striking result of estimating a value of time as a function of both income level and the amount of time saved is the large drop in the value of time compared to either the constant value of time or the value of time as a function of income level. This change is clearly the result of the modification of the total benefits function to keep total benefits non-negative. The total value of time saved as a function of income level and amount of time saved is given in Table 2.

However, the analyst who attempts to use Table 2 will quickly find out that more has changed than merely the value of time. A whole new set of requirements for data on highway improvements results from the use of any value of time that is a function of the amount of time saved.

Once the value of time is a function of the time saved, however, then clearly the total amount of time saved must be known. The average value of 1 minute of time saved is dependent on whether it is the only time saved (value of 1.3 cents), part of a total of 10 minutes of time saved (average value of 23.7/10 = 2.4 cents), or part of a total of 20 minutes of time saved (average value of 59.6/20 = 3.0 cents). (These numbers are taken from Table 2.) Because motorists on short trips can be expected to have less total time saved by highway improvements than motorists on longer trips, the motorists using a highway improvement would need to be segregated by their total trip length (and perhaps ultimately even by origin and destination). Similar problems exist for spot improvements in intersections, stop signs, or pavement quality.

All at once the highway economist needs more information than just information on the amount of time saved by the highway improvement and the volume of motorists who will use it and their income levels. He needs cross-tabulated information on the motorists' income, trip length, and all improvements (actual and possibly planned) on their different trips.

Thus, the use of Table 2 imposes data requirements far in excess of those presently available for highway economy studies. Yet at times even accurate estimates of the volume of motorists using an improvement are difficult to obtain. The result is certain to present highway economists with a challenge. Our function has been to estimate the value of time implied in the behavior of urban commuter motorists. The highway economist must now develop and test for himself how to best make use of this behavioral information in furthering rational highway planning, design, and development. Subsequent reports will describe research on the value of time for trip purposes other than commuting.

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Appendix

REFINEMENT OF THE ROUTE-CHARACTERISTIC DATA

In the study cited previously (3), it was argued that the amount of time saved as measured by the test vehicle differed from the amount of time saved perceived by the motorist in making his route-choice decision (and thus from the proper variable for an indifference curve analysis) by randomly distributed perceptual errors. An analysis of the effect of the type of error distribution showed that the estimated value of travel time saved was lowered from the one perceived by the motorist, i.e., the "true" value of time. Unfortunately, there is no scientific way to eliminate truly random perceptual errors from the data.

On the other hand, certain measurement errors that potentially could be eliminated and have the same effect as the perceptual errors were thought to exist in the measured data. Therefore, an extensive reanalysis of the data was instituted to try to eliminate or to reduce the magnitude of these measurement errors. Because measurement errors could also occur in the reported data, they were studied further.

The technique for refining the data started by identifying a subset of the data on which the analysis would be concentrated through a comparison of the measured travel time with the reported travel time. The data points for which there were important deviations between the measured and reported travel times were identified for further analysis. The subsets of the data points that were identified by these comparisons were then refined in two ways. First, the data were researched and if a reason could be documented for changing either the reported or measured data, a change was made. However, if no reason existed, the data were not altered but were kept in the data base as before. This analysis resulted in the "adjusted" data base. Second, in the adjusted data set, those data points were eliminated where large discrepancies still existed between the measured and reported time saved. The resulting data became the "filtered" data base.

After the errors had been analyzed, possible biases in the reported travel times were studied. Biases are hypothesized to occur because motorists tend to "improve" the route they choose in reporting travel times. The effect of the bias is to increase the estimated value of time.

Adjusted Data

The criteria used to identify deviant data for adjustment were as follows:

1. Instances where the reported and measured driving times for a motorist differed by 10 or more minutes in at least three out of four possible comparisons, i.e., the toll road in the morning and evening and the free road in the morning and evening.
2. Instances where the time saved on the toll route (sometimes negative) estimated by the measured data differed by at least 10 minutes from those estimated by the reported data. The morning and evening trips for each commuter were treated separately.

These data points were placed into a subset for further examination. Intuitively it is felt that these data points are the ones most likely to contain errors and biases.

After the data points in this special set had been identified by either criterion, each point was reexamined for errors that might have been introduced during the data collection and processing phases. Four basic sources of error were identified in this manner (the first three occurred for both reported and measured data and the fourth occurred only with the measured data set); they can be listed as (a) respondent misunderstood questionnaire; (b) interviewer error; (c) coding errors, e.g., keypunch errors; and (d) measurement errors caused by driving incorrect route, driving at incorrect time of day, or other measurement functions.

Although most of these error sources had been corrected in the original analysis of the data, the current reanalysis of these errors resulted in adjustments for approximately 12 percent of the measured data points and 4 percent of the reported data.

Next, the deviant data points were examined to see if the measured rush hour travel times might have been atypical. Variations in measured traffic flow from typical traffic flow conditions could result from fluctuations in the daily rush hour conditions. Because

TABLE 4

ESTIMATES FOR ORIGINAL AND ADJUSTED DATA SETS BASED ON LINEAR MODEL[a]

Model	Sample Size	Percentage Correct Predictions	Value of Time Saved (dollars per hour)	Standard Error (dollars per hour)
Original reported data	812	85.6	3.82	0.82
Adjusted reported data	807	85.3	3.78	0.92
Original measured data	529	75.8	1.82	0.40
Adjusted measured data	510	78.0	2.83	0.87

[a]The linear model contains the three basic variables (toll per person, income level, and incremental time saved for the reported data) plus the variables of sex of driver and model year of car for the measured data.

only two measurements of traffic flow for a particular route at a single time of day were taken, these variations might not have yielded representative average flows.

Analysis revealed that many of the large deviations between measured and reported time saved were bunched in the same area of a city and were all based on the same test-vehicle measurements. Therefore, when a number of commuters in a specific local area reported travel time savings that had large (more than 10 minutes) and consistent differences from measured travel time saved, all in the same direction, it was decided to adjust all the measured points from that specific locale by the average difference. Individual differences between reported and measured time were not eliminated. The average measured time saved was made to equal the average reported time saved only for the sum of estimated times morning and evening, toll and free routes, for all drivers in that section of the city.

An additional 12 percent of the measured data points were affected by these adjustments. In total, then, approximately 24 percent of the measured data and only 4 percent of the reported data were adjusted. The model was run with these adjusted data sets and new coefficients were estimated. The results are given in Table 4. The estimates based on the adjusted reported data are affected only slightly by the adjustments. This result was expected because of the small percentage (4 percent) of adjustments to that data set.

Both the estimated value of time and its standard error increased considerably for the adjusted measured data, from \$1.82 per hour to \$2.83 per hour and from \$0.40 per hour to \$0.87 per hour respectively. As a result, the difference between the measured and reported values of time decreased approximately in half.

Filtered Data

The identification of a data point for possible adjustment did not automatically mean that the point would be adjusted. Adjustment was made only if specific evidence supporting an adjustment was found. Consequently, a number of data points that could be classified as extreme or apparently inconsistent points were left in the adjusted data base. The filtering process identified these points and eliminated them to test their effect on the value of time estimates. Two filtering criteria were used as alternative approaches.

The first filtering criterion (method 1) was the removal of both estimated and reported data points where there was more than 10 minutes difference between the measured and reported amount of time saved by use of the toll road. The morning and evening data were treated separately. The justification for this criterion is purely intuitive. A difference between the measured and reported amount of time saved of more than 10 minutes is probably not due to normal perceptual or measurement variations; it is probably the result of an error in some part of the data collection and analysis tasks.

The second filtering criterion (method 2) was removal of those data points where the free-road travel time was less than the toll-road travel time. With travel time the only route characteristic (other than toll) in the estimator, presumably there is no "reason" for a commuter to pay the toll except to reduce driving time. [In the previous study (3), possible reasons were examined by including such variables as distance, congestion,

TABLE 5

FILTERING RESULTS

Data	Filtering Method	Value of Time Saved (dollars per hour)	Standard Error (dollars per hour)	Sample Size
Reported	None	3.78	0.92	807
	No. 1	4.13	1.06	709
	No. 2	3.87	1.02	436
Measured	None	2.83	0.87	510
	No. 1	5.78	2.76	412
	No. 2	4.04	1.55	394

and perceived safety in the models, but they had unsatisfactory standard errors or signs on their coefficients and were therefore excluded from the final models.]

The estimates of the value of time using the filtered (and adjusted) data are given in Table 5. The table shows that the value of time based on reported data changes only slightly under either filtering technique. However, the value of time estimated from the filtered measured data significantly increases under either filtering criterion. In both cases the value of time based on measured data exceeds the value of time based on reported data.

In analyzing the effects of filtering on the measured data base, it was evident that method 1 served mainly to eliminate data points that showed large amounts of time saved. Large amounts of time saved have a lower value of time per hour than medium (5 to 15 minutes) amounts of time saved. The results given in Table 5 are consistent with the elimination of lower value-of-time data points by method 1.

In method 2 the filtering served to eliminate "negative" values of time, i.e., commuters measured as paying to increase their travel time. The elimination of such points resulted in increased values of time.

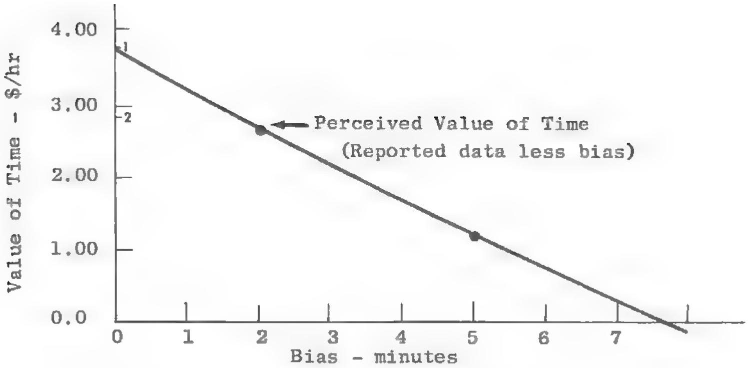
For both practical and theoretical reasons the filtered data base does not yield results appropriate for use in estimating the variable values of time. However, analysis of the filtered data serves to increase confidence in relying on estimates based on the reported data set rather than on those based on the measured route data set.

The Effect of Biases in the Reported Data

The hypothesized biases in the reported data cause a shift in the data that raises the estimated value of time. The time saved on the toll roads is hypothesized to be reported as larger than the motorist originally perceived if the toll road is used, and is reported as smaller if the free road is used. This bias serves to justify or rationalize the motorist's choice in his own mind as he is interviewed. It is accentuated by his tendency to round reported times to multiples of 5 minutes. In the decision to round up or down, the motorist's route choice can easily influence his implicit decision on which way to round.

Although the bias is obvious from an overall comparison of reported and measured time saved, there is no evidence on the actual bias in each data point. However, the overall sensitivity of the estimates of the value of time to the hypothesized biases was tested as follows: The existence of a uniform bias was first hypothesized and then eliminated by subtracting a uniform amount of time from every toll-road time savings if the toll road had been taken and by adding to every toll-road time savings if the free road had been taken. Then a new route choice model and a new value of time were estimated from the revised data. Three estimates were made using 2, 5, and 8 minutes as the level of bias to be subtracted or added to each trip.

The estimated values of time are shown in Figure 5. The decreases in the value of time are exactly as had been predicted. As more bias is removed, the value of time decreases further, reaching zero between 7 and 8 minutes. This analysis also allowed an estimation of the maximum magnitude of the bias in the reported data, based on the assumption that the adjusted measured value of time of $2.83 per hour is a lower bound on the value of time. A uniform bias of only 1.6 minutes would decrease the reported



[1] Adjusted Reported Value of Time = $3.78/hr (includes assumed bias)
[2] Adjusted Measured Value of Time = $2.83/hr

Figure 5. Effect of bias on the value of time.

value of time to this value. The conclusion is that the level of bias in the reported data is relatively small, which is fortunate because the value of time appears to be very sensitive to bias, i.e., a uniform 2-minute bias decreases the value of time by $1.14 per hour.

Summary of Adjustments to Original Data

The previous study (3) had estimated a value of time based on measured time saved of $1.82 per person per hour and a value of time based on reported time saved of $3.82 per person per hour. In this section the measured and reported data were reanalyzed and "adjusted" and "filtered" to test the effect of measurement errors and to eliminate them when possible. New coefficients were estimated for each of these revised data sets, and new values of time were calculated. In addition, the sensitivity of the value of time to biases in the reported amount of time saved was analyzed.

The results of these analyses were minor changes in the constant value of time based on the reported route data but were major changes in the value of time based on the measured route data. The changes in the value of time based on the measured route data (adjusted or filtered) brought it roughly into line with the value of time based on the reported data.

The overall conclusion is that the reported adjusted data are the best single data set on which to estimate the value of time given the limitation in the collection of the measured route characteristics.

Discussion

THOMAS E. LISCO, Chicago Area Transportation Study, and PETER R. STOPHER, Northwestern University—This paper documents some of the continuing research work being done by Stanford Research Institute in its program of determining time values for automobile travel. The work done by SRI on this subject has made exceedingly important and useful contributions to the field of transportation analysis. Perhaps first and foremost, this work has been an important contribution to the field of highway economy studies, because it has tended to make people more aware of the tremendous value of travel-time savings resulting from highway investments. In the past these savings, which are usually the greatest single benefit of highway investment, have tended

to be badly underrated and, at worst, totally ignored. The SRI work has shown in convincing fashion that commuting motorists, certainly, put a very high value on travel-time savings.

This SRI research has also made important contributions, specifically to the field of travel-time evaluation studies and generally to travel-demand modeling. This has been done by analyzing situations and using statistical methods that represent the best of both that are presently being used in the field.

In choosing route-choice analysis for deriving travel-time value, SRI has chosen a subportion of the more general mode-choice analysis, which is now widely throught to be by far the most fruitful area for deriving accurate values of travel time. In addition, this research has used disaggregate behavioral analysis, rather than aggregate models, to reach its conclusions. There is also general agreement in the transportation-analysis field that the great advances in accuracy and dependability that we can expect in demand modeling in the coming years will be in just such disaggregate behavioral models. Finally, this work has used the statistical tool of logit analysis in fitting the models used. There is also general agreement developing among researchers that logit analysis is one of the most dependable and accurate statistical tools available to analyze route and modal choice situations.

In this particular paper, the authors have reanalyzed data that they originally analyzed and reported on elsewhere (3). In this reanalysis, the authors have done basically two things. First, they have reworked the data to try and eliminate some problems that were apparently unresolved by the original analysis. Second, they have extended their modeling efforts to try and yield not one given value of time, as had been done in the original study, but different values of time for different amounts of time savings and for motorists having different incomes. Both of these further analyses appear to require some comment.

Reworking of Base Data

A basic problem of the original SRI analysis was that time values derived from the analysis of measured travel-time data differed from time values derived from the analysis of reported travel-time data. This problem was resolved in the original report by simply taking an average of the two results.

In the work reported in this paper, the authors tried to find out why there were differences. It seemed likely to them that the differences were caused by errors in the data. To try and eliminate such errors, the authors reworked the data in two ways. The first they called "adjustment" and the second, "filtering".

In the adjustment process, data were carefully examined, and changes were made either in the measured or in the reported data when a good reason could be documented for doing so. Such reasons included interviewer errors, coding errors, and errors where large numbers of persons in a given area of a city consistently disagreed in their reporting with the objectively measured data. In this last instance, the assumption was made that the measurement was wrong. We find no particular fault with this adjustment process. It raised the value of time for measured data from $1.82 per hour to $2.83.

The filtering process seems to have serious problems, however. In this process, the authors removed from the data set all instances where measured and reported route-choice travel-time differences differed by more than 10 minutes, and instances where use of the toll road represented no travel-time savings.

This procedure could have no result but to eliminate inappropriately the effect of a well-known and standard phenomenon whereby persons tend to bias their reporting of travel time between alternative routes in favor of the route that they use. This bias causes considerable differences between values of travel time inferred from route choices and driver reports of travel time as opposed to values inferred from route choices and empirically determined travel times.

Rather than try and resolve the implications of this perceptual problem, the authors have tried to resolve differences between data sets in order to be able to claim that the problem does not exist. They effectively changed the measured data until the measured data were essentially the same as the reported data. That the time-value results of the

changed measured data then more closely approximated those of the reported data should have come as no surprise. Their conclusion that this result justifies using reported data is insupportable.

Value of Time by Amount of Time Saved and by Income Class of Driver

It appears as though the authors have caused themselves some unnecessary problems because of the complexity of the argument used to obtain a value of time. The simplest way of obtain the value of time from a mode or route-choice model is to determine the coefficient of the time difference that will allow cost and time to be added together as a single parameter. Such a coefficient is the necessary scale or equivalence value between cost and time, i.e., the value of time. Thus, in the original model obtained by the authors,

$$f(x) = a_0 + a_1c + a_2(t_2 - t_1) + a_3I \tag{1}$$

the value of time is obtained by reexpressing this as

$$f(x) = a_0 + a_1\left[c + \frac{a_2}{a_1}(t_2 - t_1)\right] + a_3I \tag{2}$$

where a_2/a_1 is the value of time.

To illustrate this, the changes in f(x) resulting from a unit change in either cost or time difference can be investigated. A unit change in time difference will make a change of a_2 units of f(x). This change could be produced by a change of a_2/a_1 units of cost. Thus, the value of time may be inferred as a_2/a_1.

It is the greater complexity of the authors' derivation that led to the abortive effort of attempting to incorporate polynomial terms in income and time difference. Given the original hypothesis of the value of time, the polynomial model is a logical step. Unfortunately, high intercorrelations between the variables [e.g., between I and $I(t_2 - t_1)$] and the use of five instead of three variables both lead to the estimation of a less reliable model than the original one. These two factors are probably largely at the root of the four reasons given by the authors for a disappointing model.

The hypothesis of the form of the variation of total benefits with time saved is only one of several possible hypotheses. It poses some serious problems in the evaluation of alternative plans. The S-shaped benefits curve suggests that benefits accrue over only a restricted range of time savings. Both small and large time savings apparently yield no increased benefits. One immediate question that is raised by this is how to treat a series of improvements on a particular link. If each is evaluated separately, then total benefits for each may come from the first part of the curve, and may sum to a relatively insignificant value. However, taken together they may produce significantly higher total benefits, because total time savings may then occur in the second, steeper portion of the curve.

The piecewise estimation does not appear to vindicate the hypothesis. In the equations derived there are both Δt and $I\Delta t$ terms, and it would be useful to know how high the intercorrelations are between these terms. To interpret the weight of each of the terms, the β-coefficients ideally should be used, and these would give a more reliable basis for interpreting the equations. The unacceptable results of the piecewise estimates for both the 0 to 5 and 5 to 15 minute time savings are probably due to the paucity of data on these small time savings and to the comparatively large size of minimum toll charges. Because the minimum toll that can be paid is 10 cents, it is extremely dangerous to try to extrapolate data back beyond this point.

To avoid problems of collinearity in the estimating equations, an alternative method of model calibration could be used to determine variations in value of time with income. This method would be a stratification of the data by income groups. Separate models could be constructed for each income group and the variations in the resulting cost and time coefficients could be analyzed across all income groups. This approach has been

successfully used in previous research (4). Then the results of attempting to determine variations of the value of time with time saved may well be markedly different.

In general, it appears that the authors have adopted an overly complex method of dubious validity to determine their final values of time. This method has brought with it several further problems in terms of attempts to value time with respect to time saved and trip-maker's income. Finally, some highly sophisticated statistical manipulations have been attempted that are probably well beyond the sophistication of the data base. It was not unreasonable that the authors found the results of these manipulations to be untenable, and subsequently discarded them. The hypothesis of the variation of value of time (total benefits) with time savings was not validated by the empirical results until considerable further assumptions and adjustments had been made to these results.

The basic requirements of model-building are accuracy and simplicity. It does not seem as though the models of total benefits presented in this paper are simple, and their accuracy is not proved. The difficulties of use of these values may alone render them of little practical use. Our abilities to predict travel movements to the degree of precision where we can identify each user and his exact time saving, as required by this model, do not currently exist. Furthermore, it is not obvious that they should be developed for the foreseeable future.

Reference

4. Stopher, P. R. A Probability Model of Travel Mode Choice for the Work Journey. Highway Research Record 283, 1969, pp. 57-65.

THOMAS C. THOMAS and GORDON I. THOMPSON, Closure—Two research groups studying the value of travel-time savings to commuters used data on individual traveler's transportation choice. Both arrived at a constant (marginal) value of time within a few cents of each other. Both had a large intercept term favoring one route when there was no difference in travel time between the different routes. One study found one route to be preferred over the other by about \$2.00, while the other found a preference of about \$0.40.

The first study (Lisco) used mode-choice data. It concluded that it was reasonable to assume that the full estimated \$2.00 preference of an average motorist for the automobile over rail rapid transit could be explained by convenience, scheduling, and other factors. The second study (SRI) used route-choice data. It could not see any reason why the average motorist would have to be paid \$0.40 to use the toll route given no time difference between routes, because the engineering quality of the toll route was higher than the free route.

SRI had previously developed (and reported in the literature) theoretical and empirical data that showed the value of travel time was not constant for different amounts of time saved. Therefore, the constant (marginal) value of travel time was seen as only a first approximation to an S-shaped function. Because the route-choice data showed a \$0.40 intercept, it is clear that the use of this first approximation could cause substantial errors in estimates of the true value of travel-time savings.

It is "unfortunate" that both SRI's theoretical work and its selection of a route-choice model makes the holding of the assumption of a constant value of travel time impossible. As the discussion points out, "The difficulties of use of these values may alone render them of little practical use." However, as our paper points out, we took as our task exploring the determinants of the value of travel time, not the making of assumptions on the capabilities of transportation economists to use them.

On the specific question of the ways the estimates were made, the following is offered:

1. The dependence of the value of travel time on income was estimated by the use of polynomial terms and also (as the discussion suggests) by the breaking of the data base into income categories. Only the results of the former analysis were reported

because of their superior statistical characteristic (considerably smaller standard errors). However, there was little difference in the maximum likelihood estimates.

2. The discussion suggests that simple models are the best—they were used first. The simplyfying assumptions were removed (such as linearity) only when the result showed the assumptions to result in large errors. Simplicity and accuracy is highly desirable; simplicity at the expense of accuracy is not desirable.

3. The discussion objects to the process of filtering the data, but accepts the process of adjustment. We agree with this and for this reason the adjusted data, not the filtered data, were used in the analysis. The filtered data are used in the Appendix only to highlight certain characteristics of the data.

4. The difference between the value of travel time based on different data sources is not seen as a "problem". Rather it confirms the theoretical analysis and serves to highlight underlying issues in the analysis of values. The two estimates operate to bracket the true value of travel time and greatly increase the confidence that can be placed in the estimate.

5. The discussion incorrectly states that, in the paper, "Both small and large time savings apparently yield no increased benefits." As is clearly shown in Table 3, we only argued that time savings less than 5 minutes or greater than 15 minutes have a smaller value per minute than those between 5 and 15 minutes; i.e., the relationship between the value of travel time and the amount of time saved is S-shaped.

6. It is also stated in the discussion that the results of the piecewise estimates between 5 and 15 minutes are unacceptable. Statistically we see them as highly acceptable, and we can find no basis for such a statement.

However, these are minor points. As stated initially, the major difference is that Lisco and Stopher do not accept what to us is a demonstrated empirical fact: that the value of travel-time savings is not a constant, but is dependent on the actual amount of time saved. The assumption of a constant (marginal) value of travel time leads to a large error in pricing time savings, especially for small amounts of time saving, i.e., less than 5 minutes. This is the primary issue that the reader will have to judge for himself.

Congestion Toll Pricing for Public Transport Facilities

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Economists, policy-minded administrators, and planners are turning increasingly to congestion toll pricing as a practical and efficient instrument for solving the traffic congestion problem. However, in their advocacy of short-run marginal cost pricing as a replacement for the present method of roadway pricing (which for the public highway system approximates short-run average variable cost pricing), economists and others have generally relied on an over simple theoretical world in reaching their conclusion about the efficacy of marginal cost pricing. Rather than contend that marginal cost pricing is not the best method of pricing, this paper argues that it is not yet clear that marginal cost pricing is better than our present type of pricing policy.

•IT WOULD APPEAR that the case and particularly the public arguments for marginal cost pricing have sometimes, if not often, failed (a) to view short-run marginal cost pricing within a longer-run context and thus to view our pricing and investment policies as an inseparable package; (b) to properly consider some money and non-money costs and effects stemming from the abandonment of our existing pricing system in favor of a marginal cost pricing system; and (c) to consider the incidence of one pricing system versus another (in the sense of "who gains and who loses").

Within these introductory remarks three other aspects of the so-called pricing problem deserve mention. First, although most of the discussion in the transportation literature, and certainly in this paper, deals with roadway pricing, the principles and issues should be regarded as a more general matter having applicability to virtually all types of transport systems. Second, it should be recognized but too seldom is that congestion in urban areas is not confined solely to highways and does not affect just the users of automobiles, trucks, and buses. In fact, it can and does confront even the users of transit systems—not only as they wait in queues when entering or exiting from subways, rapid transit stations, or buses, but also as they are crowded into and thus congested within transit cars or buses. The latter type of congestion, unlike highway traffic congestion, will not add greatly to the passenger's travel time (other than an increased wait to get onto and off transit cars or buses and an increased time for intermediate station stops), but it can and often does markedly affect his level of discomfort by virtue of the additional crowding. Furthermore, in these crowding situations, just as for highway congestion, each additional individual transit user (for a given time period) is causing the total costs to all transit users to increase more than the private cost he faces. In short, if a person jams onto a subway car, not only does he suffer the discomfort of the "crush", but he also causes the other occupants of the car to suffer additionally from his entrance. Thus, arguments about highway users causing congestion for all other highway users are entirely analogous to additional transit users with respect to their crowding and comfort levels.

Third, some supporters of marginal cost pricing (often referred to as congestion pricing) assume that traffic congestion is intolerable and therefore the problem is to

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reduce traffic congestion, regardless of all else, and that any measure to reduce traffic congestion—whether it is the imposition of congestion tolls to reduce traffic flow or to shift users from automobiles to transit modes or to shift their travel hours from the peak to off-peak periods—is better, a priori, than existing conditions. To the contrary, there are three choices open to society: (a) continue to endure congestion, whether on jammed highways or in crowded transit vehicles; (b) reduce the traffic flow or passenger ridership, whether through pricing mechanisms, administrative controls, or physical barriers; or (c) expand the highway system capacity or number of transit lines, vehicles, or trains. The wisdom of the second or third alternative relative to the first will depend principally on the extent to which congestion will be reduced, on the value of this reduction to those enjoying faster travel or reduced crowding, on the disbenefit to those "forced off" or affected by those "forced off" the facilities should the second alternative be adopted, on the extra travel benefit accruing to new users, and on the cost or resource commitments necessary to expand the system capacity should the third alternative be adopted. Furthermore, there will be equity and income redistribution considerations that should enter the decision-making process.

The remainder of this paper will examine the consequences of different pricing policies by focusing on (a) identification of the "gainers" and "losers" with respect to marginal cost versus average cost pricing, (b) consideration of the costs associated with implementing different pricing schemes, (c) the efficacy of imposing marginal cost pricing in situations when the roadway system is considered as fixed or unexpandable for all time, and (d) the short- and long-run adjustment problems stemming from expansion and the abandonment of average cost pricing in favor of short-run marginal cost pricing. Importantly, though, this discussion will deal only with the non-backward-bending or non-reducing capacity case for transport facilities (1, 2, 3).

SHORT-RUN CONSIDERATIONS

"Gainers" and "Losers" for Different Pricing Policies

Most economists argue that short-run marginal cost pricing will lead to maximization of net benefits. This consideration is generally founded on the assumption that marginal cost pricing prevails throughout the economy, and that the costs of implementing such a pricing scheme and of countering any adverse effects on employment and income distribution are negligible. In such a simplistic world, even I would agree. But such is not the case and, as often noted, other objectives (4, 5) might be ill served by a sharp reversal of the existing average cost type of pricing policy and a move to marginal cost pricing.

To explore this last point, we can make use of the cost, price, and demand relationships shown in Figure 1. Assume that the variable cost curve includes not only the variable supporting-way and vehicle operating and maintenance costs (and other similar expenditures that vary with the flow rate) but also the costs for travel time, effort, discomfort, and safety

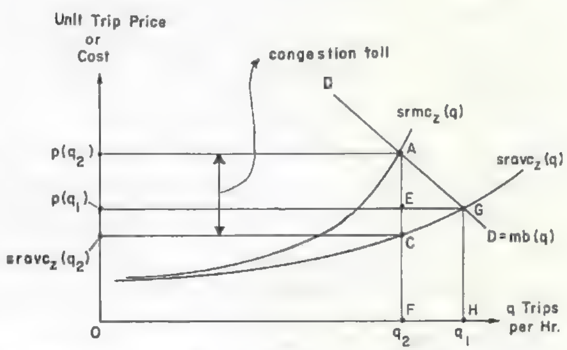

Figure 1. Cost, price, and demand relationships: $srmc_z(q)$ = short-run marginal costs for flow q on facility z; $sravc_z(q)$ = short-run average variable costs for flow q on facility z; DD = demand function for facility z = mb(q); p(q) = price for flow q (for certain pricing policies); $sratc_z(q)$ = short-run average total costs for flow q on facility z; and mb(q) = marginal benefit for flow q on facility z.

NOTE: These curves can be applied with equal validity to both highway and transit travel. In the former case, q can be regarded as the hourly vehicular flow on a particular highway; the increase in variable costs with increases in q stems mainly from increased travel time. In the latter case, q can be regarded as the hourly passenger flow arriving at a particular bus stop or rail transit station; the increase in variable costs with increases in q stem partially from increased travel time but mainly from increased crowding and discomfort as buses or trains become overloaded (relative to the number of seats). In the short run, the highway vehicular capacity should be regarded as fixed.

hazard that are incurred by travelers; assume further that, under the pricing policy now practiced for highway and transit systems, the traveler in deciding whether to travel and how much to travel perceives his trip payments to total and be equal to the short-run average variable cost. More specifically, I have assumed the following:

1. For a given highway trip, users perceive the variable user gasoline, tire, and parts taxes equally and as part of their complete money-time-effort payment. These taxes are assumed to be variable with respect to the quantity and length of trips but uniform per vehicle-mile. Also, the unit variable user gasoline-tire-parts taxes are assumed to be just equal to the unit variable costs for operating and maintaining the highway (which are assumed to be constant for all levels of flow).

2. For transit travel, it is assumed that the transit fare is perceived by transit users and that it is just equal to the unit variable costs for operating and maintaining the transit system. Also, for highway travel, the complete money-time-effort variable costs increase at an increasing rate because of the increase in congestion and travel time with increases in flow q, whereas for transit travel the increasing rate stems from increases in congestion and passenger discomfort (resulting from crowding) with increases in flow q. In the latter case, as a bus or as the cars of a rail transit train become more and more crowded with increases in the passenger load (that is, with increases in q), not only will crowding and discomfort increase but travel time will also because of the stops required.

These sets of assumptions are made mainly for convenience and may do some violence to the actual facts; that is, it may well be that the highway-user tax in some instances more than covers the highway maintenance and operating costs and in some cases less. Similarly, transit fares may sometimes cover more than the transit maintenance and operations expenses and others less. For many dense urban situations, however, I suspect that these assumptions are not far from the truth.

With reference to Figure 1, it is evident that if we switched from the present average variable cost type of pricing policy to marginal cost pricing (while ignoring the costs of implementing a workable marginal cost-pricing system), some of the existing q_1 travelers (or q_1 minus q_2 travelers) would be unable or unwilling to pay the toll AC that would be required to bring about marginal cost pricing. In the short run these q_1 minus q_2 users would suffer a loss as they switched to a less preferable mode, to a less preferable hour of travel, to a less preferable route, or to less travel (e.g., they decided to travel less often or not at all). Furthermore, all of the q_2 users—even though able and willing to pay the toll of AC—would suffer a unit loss of AE with marginal cost pricing (relative to an average variable cost-pricing policy); that is, although their unit congestion costs would be reduced by an amount EC when the volume was reduced from q_1 to q_2, their money payments would be increased by AC, an amount that would exceed the reduction in congestion costs by unit amount of AE. Thus, all of the users in the short run—those continuing to use the facility and those forced off of it—are worse off. (It is presumed throughout that motorists are homogeneous with respect to time and congestion values and costs.)

The obvious question arises: How can net benefits to society be increased when the benefits to all users of the facility are decreased by a switch to marginal cost pricing? The problem is simply that the increases in net benefit have been extracted from the q_2 users in the form of tolls and (presumably) have been transferred to other parties, political groups, or the like. Thus, the users have suffered a loss, individually and in aggregate, but those receiving the tolls and society in aggregate have received a gain. Needless to say, the imposition of marginal cost pricing would hardly induce the users to look on the results as "optimum" or "efficient" and it is likely that they would view the matter as highly inequitable, at least in the short run. Finally, I would point out that there may be other losers as well; that is, some, if not most, of those users unwilling or unable to pay the toll required by marginal cost pricing would shift to other routes, other modes, or other times of day. In the process, they would usually increase the travel time, congestion and/or crowding on those other routes or modes, both for themselves and for the other users.

Practicalities and Costs of Different Pricing Policies

The Highway Case—When considering the wisdom of abandoning average variable cost pricing in favor of marginal cost pricing, it is necessary to develop a pricing system that will inform users, in advance of their making a trip, about the marginal cost prices they will face if they decide to travel. To develop a system in which the prices would be hidden or in which users are billed later in some aggregate fashion (e.g., by receiving monthly bills) would tend to defeat a major purpose of marginal cost pricing, namely, to ensure that users are aware of the costs stemming from additional trip-making. Ideally, of course, the pricing system would be pervasive with respect to all facilities, modes, times of travel, and so forth. Prices for given facilities would change from hour to hour and from day to day as the equilibrium flows and marginal costs would change in response to fluctuations or changes in demand. And certainly the system should reflect the demand relations for each mode of travel during each hour of the day as well as the cross-relations with respect to other modes and times of day for trip-making. However, were such a flexible and pervasive pricing system to be instituted—and one can hardly argue otherwise if the case for marginal cost pricing is to have a solid basis—it seems evident that an extensive and expensive toll-collection system would be required.

Although many types of electronic toll-collection systems have been talked about, whether they can be practically developed and applied remains to be seen. (Again, a necessary requirement would be that prices for trip-making be known in advance.) In the interim, of course, it would be possible to use the usual tollgate-type system for implementing marginal cost pricing. On the one hand, the use of tollgates on roadway systems would ensure that users are confronted with the actual short-run marginal costs rather than permit some people to travel even though their marginal benefit is less than the marginal costs for volume rates of that magnitude. But, on the other hand, to institute de novo a tollgate or other system would require resource expenditures not only for the construction and operation of tollgates, but it would also cause the system users to suffer additional travel-time delays and time costs while waiting to be serviced at the tollgates. [Of course, delays at tollgates could be reduced to virtually nothing if sufficient extra tollbooths were provided and operated. There is an obvious trade-off between short-run travel-time delays and long-run tollgate costs, although it is presumed that the most efficient gate capacity would result in some queuing delays.]

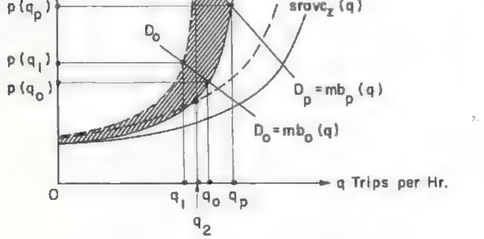

Figure 2. Short-run cost, demand, and pricing relationships for marginal cost pricing: D_p = demand function for hourly flow during peak periods; D_o = demand function for hourly flow during off-peak periods.

The full marginal costs, to include the variable costs of implementing and being delayed by a marginal cost-pricing system, may be represented somewhat as shown by the $srmc'_Z$ (q) curve in Figure 2, where $srmc'_Z$ (q) equals the short-run marginal cost, including pricing implementation and delay costs, for facility z at volume rate q. These costs together with the fixed costs required for the tollgates can be compared with $srmc'_Z$ (q), the short-run marginal costs for "costless" marginal cost pricing, and with the short-run average variable costs both with and without the costs of implementing the pricing system, $sravc'_Z$ (q) and $sravc'_Z$ (q) respectively. Relative to costless marginal cost pricing, the full marginal costs will cause the peak and off-peak period costs and prices to be increased, thus reducing the hourly flow from q_p to q_2 during peak periods and from q_o to q_1 during off-peak periods. The comparisons between hourly flows and between net benefit totals for different pricing policies will be made by using the costless marginal cost curve and pricing policy as a base. This base

is used in order to simplify the graphical illustrations of the changes in total net benefit. (This assumes, of course, that the hourly demand throughout the day can be represented by hourly demand functions for just two time periods. Also, this representation ignores the cross-relations between peak and off-peak time periods, two obvious oversimplifications.)

At this stage of the analysis it is appropriate to ask whether, in light of the additional travel delays and toll collection costs, marginal cost pricing still appears to be the most efficient pricing policy. Obviously, the answer depends on what other alternative pricing schemes and pricing policies are available. But it is of utmost importance to note that, given these broader and more realistic conditions accompanying the advocacy of marginal cost pricing, one can no longer argue a priori that marginal cost pricing—even in a perfect economic world—is or is not better than even average cost pricing or quasi-average cost pricing.

Alternatively, the present pricing policy for most public roads might be looked on as a quasi-average total cost pricing scheme in which the perceived roadway price is equivalent to the uniform user tax plus the short-run average variable cost or $sravc_Z(q)$. This view is somewhat different from that adopted earlier for the general comments about the effects of different pricing policies. Here it is implied that the present highway user taxes cover more than the variable facility operating and maintenance expenses. In fact, many would estimate that, for the highway system in aggregate or for that within central cities (again, taken as a whole), user taxes in total cover both the fixed and variable costs for the facilities and their use (6, 7, Tables 4 and 5). For these assumptions, the price to the user would be represented by the $srtvc_Z$ (q) curve shown in Figure 3. Of considerable importance, however, the costs of administering this pricing policy for highways and of collecting the user prices (uniform tax plus the user's expenditures of time and effort) are virtually nil, particularly because travelers are not delayed by the collection scheme. Thus, as a practical matter, the average variable cost plus uniform tax pricing policy is costless for highways. Relative to costless marginal cost pricing, as represented by $srmc_Z(q)$, we would usually find that hourly flows and congestion during peak periods would be too high and during off-peak periods would be too low. [Of course, the uniform tax level could be set high enough to result in a marginal cost price being charged during peak (and off-peak) periods, with an overall price of $p(q_2)$ and flow q_2 as shown in Figure 2. However, flow during off-peak periods would be far too low. On an a priori basis, no conclusion can be reached about the "best" or "better" level for the uniform tax.] Relative to costless marginal cost pricing, this average variable plus uniform tax cost pricing scheme would cause hourly losses in net benefits during the peak and off-peak periods roughly as shown respectively by the right and left shaded areas in Figure 3. [The losses in net benefits are equal to the difference between the total net benefits for the pricing policy in question and those for the costless marginal cost pricing policy. Total net benefits for any given pricing policy are defined as the difference between total benefits and total costs, the latter to include any fixed costs. The total benefits may be calculated by summing the marginal benefits—or integrating under the demand curve—up to the equilibrium flow level. Total costs may be calculated by summing marginal costs up to the equilibrium flow level and then by adding them to any fixed costs, where applicable, for new or existing facilities (2, 3).] These losses can be compared to those stemming from full marginal cost pricing, which are represented by the shaded areas below the

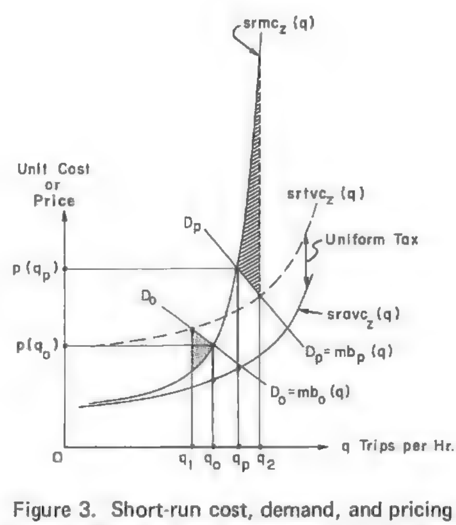

Figure 3. Short-run cost, demand, and pricing relationships for uniform user tax pricing policy.

peak period (D_P) and off-peak period (D_O) demand functions in Figure 2 plus the fixed costs required to install the tollgate or other pricing system.

On balance, it is not clear which pricing policy will result in the smallest net benefit losses, and thus only a full-scale benefit-cost analysis will indicate which of these (or other) pricing policies will be most efficient economically or will be better on other grounds. A second but equally important conclusion can be drawn with respect to pricing highway travel. That is, because the costs of administering uniform user taxes are nil, or virtually so, some user tax is preferable to no user tax or to "free" highway travel. For example, referring to Figure 3, it can be seen that a uniform tax set high enough to bring about a price of $p(q_O)$ and an hourly flow of q_O during off-peak hours will result in lower peak and off-peak hourly losses in net benefits—relative to costless marginal cost pricing—than would a zero uniform tax.

The Transit Case—The situation for transit facilities is somewhat different from that for highways, other than for the case of "free transit". That is, except for free use of transit facilities, there is no way of administering either a uniform or differentiated price that will be costless (or virtually so) and that will not delay passengers during collection. If a uniform-fare (plus short-run average variable costs) pricing policy were to be used for the transit system, the situation would be similar to that shown in Figure 4. For this situation, the $srmc'_Z$ (q) curve represents the short-run marginal costs for facility z operating at hourly flow q, to include the variable costs of implementing the collection system and of delaying passengers while collecting fares. Curve $srfvc_Z(q)$ represents the price function faced by travelers and is the sum of the uniform fare and short-run average variable costs (to include those caused by crowding and discomfort as vehicles become more and more crowded). During peak periods, the hourly flow would be q_2 and the price would be $p(q_2)$ for this uniform fare policy and, relative to the net benefits resulting from costless marginal cost pricing as represented by the $srmc_Z(q)$ curve, the resulting hourly losses would be equal to the entire dashed shaded area plus the fixed costs for the collection facilities. During off-peak periods, the hourly flow would be q_1, the price would be $p(q_1)$, and the hourly losses (again, relative to the net benefits obtainable with costless marginal cost pricing) would be equivalent to the entire dashed and dotted shaded area lying below D_O (the off-peak demand curve) plus the fixed costs for the collection facilities.

One should ask whether the use of differential peak and off-peak period transit fares would help to reduce the above losses in net benefits. The answer, almost certainly, is yes. (This conclusion would need no qualification if the costs of administering and collecting differential fares, including delays to users, were equal to those for a uniform fare system. Although differential fares may entail slightly higher collection costs, the remarks that follow will assume that the increase is negligible. If the peak-period fare were increased so as to bring the total user price up to point A shown in Figure 4, the loss in net benefits lying between D_P (the peak-period demand curve) and $srmc'_Z$ (q) could be eliminated. Similarly, if the off-peak transit fare were reduced so as to bring the total user price down to point B, the loss in net benefits lying between D_O (the off-peak demand curve) and $srmc'_Z$ (q) could be eliminated. Although differential prices would almost certainly be more efficient than a uniform fare policy for transit facilities (in contrast to the case for highway facilities in which such a result may or may not be true), one may not assert that such a pricing policy is definitely preferable to "free transit" (that is, to a zero transit fare policy). For the free transit case, the hourly loss in net benefits relative to the

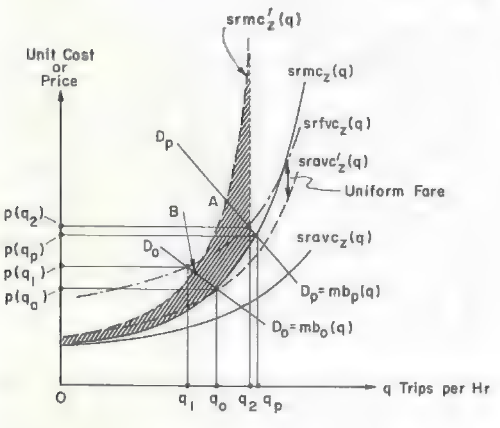

Figure 4. Short-run cost, demand, and pricing relationships for uniform transit fare pricing.

costless marginal cost pricing case would be equal to the dashed shaded area in Figure 5 during peak periods and to the dotted shaded area during off-peak periods. On an a priori basis, it cannot be argued that the sum of these shaded areas is either larger or smaller than the combined sum of fixed costs of the collection facilities and the shaded areas for either the uniform or differentiated transit price policies discussed earlier and shown in Figure 4.

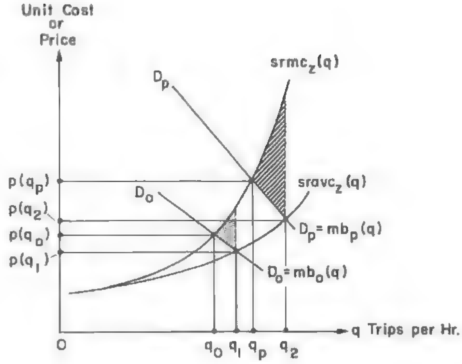

Figure 5. Short-run cost, demand, and pricing relationships for "free transit" pricing.

LONG-RUN CONSIDERATIONS

Practical Aspects of Pricing and Facility Expansion

Considerable attention should be devoted to the efficacy of imposing marginal cost pricing in situations when further expansion of the roadway system is regarded as impossible for whatever reasons and regardless of whether or not its expansion is more efficient economically. Gabriel Roth (8) seems to adopt this attitude, for example, in saying "In most cases access is provided by one road only, and the provisions of further roads is impossible because of the technical layout of built-up areas. In these circumstances competition in any area is effectively impossible. Any firm or individual owning an access road would be in a monopoly position." Perhaps to put the matter in more technical terms, one should consider pricing in broader perspective and as just one of several links in the investment-pricing-operation chain rather than as a matter for short-run consideration at the present. (To simplify the discussion of this point, the costs of implementing pricing systems will be ignored.) Also, innumerable studies and articles on the subject of roadway and congestion pricing suggest that a fundamental purpose of pricing is to reduce congestion, to lessen peaking, or to shift people from automobiles to transit. More pertinently, pricing is simply a mechanism to guide consumers in making decisions among the choices open to them, to help establish the values of products or services, and thus to aid private or public firms or agencies in their decisions about investments, operations, products, and services. (These comments are made in the context of maximizing the public's economic welfare and are aside from matters of equity and income redistribution.) In the context of the public transport problem, pricing is merely one of the instruments available to help determine how many and which kind of modal services should be provided, the extent to which the services should be offered, and the appropriate levels of operation and congestion (or, say, performance) for those modal systems. For highways, the appropriate use of pricing and the concurrent analysis of the additional costs of expansion and extra value of increased trip-making and reduced congestion can serve to guide decisions about the amount of highways and number of lanes needed. Similar trade-offs should be used in making decisions about the wisdom of direct pricing mechanisms, about the number of tollbooths (should they prove to be warranted), and so forth. For transit systems, good pricing and incremental benefit-cost analysis can aid significantly in making decisions not only about the feasibility of various modal systems, together with their route coverage and trackage requirements, but also about schedule frequency and train lengths. For the latter, transit operators can more sensibly make trade-offs between different crowding levels (and the associated loading and unloading times) within buses or trains and different bus or train frequencies, bus sizes, and train lengths rather than rely on arbitrary load factors or operating rules of thumb to make such decisions.

Pricing is a short-run proposition and it is a matter of determining day-to-day prices, given the market (as represented by appropriate demand functions), given a pricing policy, and given the actual day-to-day variable costs stemming from operation and use of a particular facility. And it is a problem of determining which pricing policy will result in the most efficient (or "maximized" net benefits) day-to-day operation and use or

volume (and thus congestion) levels. From day to day, one can do no better than maximize the daily efficiency (i.e., net benefits) of the system that is in place and in operation. But of equal clarity and importance, it is all too obvious that the system size, its service, and its operating characteristics can be altered over time, thus changing the cost functions and the resultant use, prices, net benefits, and so forth. Consequently, our concern with pricing should rest not only with the present-day, short-run operating circumstances of a given facility or system but also with the effects of long-run changes to the facilities and their operations.

To view this problem more directly, I would note that many economists, when analyzing the roadway pricing problem, have concluded that present uniform user tax levels and pricing policies have led to pricing highway travel (particularly in core areas of cities) far below short-run marginal costs and thus have led to economic inefficiency. Crucially, though, not all of these economists have appropriately analyzed either the long-run implications of this finding or conclusion or the practical considerations and costs stemming from the implementation of a marginal cost pricing system (the latter in the sense discussed in the first part of this paper). And it is here that the contradiction seems most apparent. Much to the point, economists have continually concerned themselves with economic inefficiencies stemming from poor short-run pricing policies but have sometimes failed to examine and pinpoint the manner and extent to which economic inefficiencies also can and do result from poor investment and expansion policies. Inefficiency with respect to pricing is no more onerous or important than that with respect to expansion.

Furthermore, one is inescapably led to conclude that economists, by arguing for the institution of congestion tolls set equal to the short-run marginal costs without specifically considering the long-run possibilities and implications as well, are perhaps unwittingly lending support to the usual contentions that traffic congestion must be abated; that traffic is strangling and choking the downtown and central city core areas; that the construction of more highways will only lead to more traffic, more congestion, and more strangling; that the urban highway-expansion program (particularly the Interstate highway links) should be slowed if not halted; and that more rapid transit should be constructed in place of highways. The unrest with respect to the contention that highway expansion should be slowed if not halted probably stems more from past failures to recognize and take account of certain externalities and income redistribution problems (for those dislocated or affected by specific highway locations), from failure to compensate nonusers for their social costs, from poor aesthetic designs, and from an inability (or failure) to trade off these social and external costs with higher highway location or design costs than from matters of pricing and long-run investment policy. (It should be obvious, of course, that most economists would hardly endorse such bald and unqualified contentions, and certainly not without having been provided the appropriate benefit-cost analyses to validate the views.)

It may be, for example, that traffic is strangling and choking the CBD or the central city. But such a conclusion must rest on deeper consideration of many aspects other than the mere existence of traffic congestion on streets and expressways. In the first place, the fact that workers or shoppers will actually put up with traffic congestion during certain times of day and will continue to travel by automobile—rather than forego trips altogether, rather than use mass transit (where it is available), or rather than travel at some less congested time of day—is ample proof that automobile trips during those times of day are highly valued, both in an absolute sense and relative to other available opportunities, and it is proof that reduction of automobile travel will lead to a reduction in benefits as well as in congestion costs. A related matter of some considerable importance is that automobile and mass transit can hardly be regarded as highly or even reasonably substitutable services for either work or shopping trips and that significant shifts from automobile to mass transit are not in the offing. [The evidence on these matters is far from complete and is, of course, limited to the presently available set of modal opportunities. However, the few competent studies thus far conducted bear this out. See, for example, the automobile and transit demand elasticities, with respect to automobile and mass transit travel times and costs, tabulated elsewhere (9).] As a consequence, a shift to congestion toll pricing (at short-run marginal cost)

for highways not only would, in all likelihood, reduce traffic and its congestion but also would reduce the number of person trips (and the associated benefits). Thus, a mixed blessing may result, and the city may well be crippled more by the loss of workers and shoppers (and their expenditures and contributions) than by the reduced congestion for those willing to pay the tolls. In fact, it is difficult to envision how any significant gains —other than less noise and air pollution, if these are that important—will accrue to the city itself or to its businessmen merely from having traffic congestion reduced, unless, of course, there are excess toll revenues that will be distributed to the city and its businessmen or used to reduce their taxes. In reference to excess revenues, if—as is probably the case in many and perhaps most urban core situations—the demand for highway travel is high enough to produce considerable congestion and to result in equilibrium flows above the level corresponding to that at which the short-run average total costs are at a minimum point (i.e., if equilibrium flow q is above the level q_o shown in Figure 6), abandoning the average variable cost plus user tax pricing in favor of marginal cost pricing will result in excess money revenues being generated. As can be seen in Figure 6, the revenues in excess of total costs to society would be equal to q_A times the difference between $p(q_A)$ and $sratc_x(q_A)$. Also, if the situation shown in Figure 6 is representative of urban core highway conditions at present, then so long as facilities are not improved or expanded, we can expect the excess revenues or profits to continually increase over time. These increases in profits will occur, of course, so long as demand shifts (upward and to the right) in response to population shifts, income increases, and so forth. The excess revenues alone should induce the economist and the engineer (and the "city fathers") to consider the obvious question: Should the facilities be expanded?

Clearly, to talk about the necessity or economic wisdom of instituting marginal cost pricing and to ignore government policies with respect to investment planning is tantamount to being negligent or unobjective. To put the matter more strongly, I suspect that some planners and analysts would (for noneconomic and subjective reasons) be delighted to see short-run marginal cost pricing instituted and to have the urban highway program halted even if long-run considerations indicate that it is more efficient economically to expand the highway system. In a sense, this suggests that they feel it is "impossible" or would do irreparable harm to expand the highway system within urban core areas, and thus they forego consideration of this possibility.

Effects of Expansion Under Nonconstant Returns to Scale

In a rough way, the short- and long-run effects of following different pricing and investment (or, say, expansion) policies can be examined by referring to the cost and demand relationships shown in Figure 7. Of course, even these situations and functional relationships are oversimplified, particularly with respect to the characterization of demand as static, both during the day and over the years. On the other hand, both increasing and decreasing returns to scale cases are represented.

Given cost and demand functions, such as those shown in Figure 7, one can determine which facility size or capacity will maximize net benefits over the long run by noting the specific facility associated with the intersection between the demand and the long-run marginal cost curves. (If the demand function intersects the long-run average total cost curve, one may be sure that net benefits will be positive, fixed costs included.) Or, put in other terms, facilities and, in turn, the output should be continually expanded so long as the incremental benefits are larger than the additional fixed and variable costs stemming from increased

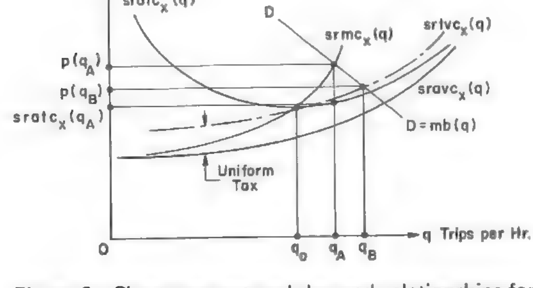

Figure 6. Short-run cost and demand relationships for a fixed facility and high demand.

capacity and output (these costs being represented by the long-run marginal cost curve). Similarly, one should reduce facilities and output so long as the loss in benefits is less than the reduction in fixed and variable costs. At the point when the marginal benefit just equals the long-run marginal cost, or point E for demand curve DD in Figure 7 and point F for demand curve D′D′, the long-run marginal cost will also equal the short-run marginal cost for the proper facility (i.e., the facility of lowest total cost for that output or q level, with facility A having lowest total cost at output level q_A and with facility C having lowest total cost at output level q_C, and will determine the most efficient day-to-day operating price. Admittedly, idealized conditions are embodied within these cost and static demand functions, and the costs and other effects of implementing workable marginal cost pricing systems are not included.

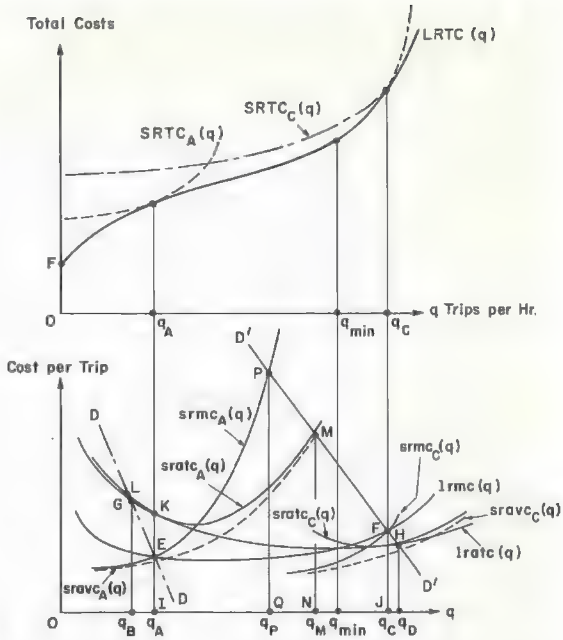

Figure 7. Long-run cost and demand relationships for other than constant returns to scale.

To follow the criteria outlined in the preceding, and to adopt facility A and output level q_A (with a price equal to EI) when the demand is DD or to adopt facility C and output level q_C (with a price equal to FJ) when the demand is D′D′, will result in maximizing net benefits to the public at large, regardless of whether a public or private facility is involved. [Using the same assumptions as before, the price is the combined time, effort, and money expense the user must forego to make a trip; furthermore, it is assumed that, aside from any toll, users perceive their time, effort, and money expense to be equivalent to the short-run average variable cost. Thus, for short-run marginal cost pricing, the toll for facility x and flow q must be set equal to $srmc_x(q)$ minus $sravc_x(q)$.] However, such idyllic planning and operating decisions will not always be forthcoming, either because of the lack of competition (both in the private and public sectors) or because of financial feasibility and pricing constraints (or, of course, because demand is hardly so static and predictable).

Were the demand level to be at DD, for example, no firm or public authority could build facility A, price its use so as to maximize net benefits (i.e., set its toll so that the total user price was equal to short-run marginal cost or EI), and cover its total costs. In fact, and even with some competition, firms or public authorities operating under these demand conditions would tend to build the minimum total cost facility for an output level of q_B or less rather than facility A. But if facility A were built by a firm or public authority, and if total costs had to be recovered (i.e., financial feasibility were a requirement), a high toll—equal to the difference between short-run average total cost and short-run average variable cost—would have to be charged. The total user price would correspond to the level indicated by point L, and the flow would be reduced to an amount slightly below q_B. Clearly, from a public point of view (i.e., from that of attempting to maximize net benefits to the public, regardless of who incurs the costs and who accrues the benefits), it would be in the interest of society to subsidize either public or private firms or authorities faced with similar demand and cost conditions (as shown in Figure 7 and indicated by demand DD) to the extent required in order to encourage proper planning and pricing. More specifically, both private and public firms and agencies should be encouraged to build facility A (for the DD demand case)

and to set the toll equal to marginal cost minus average variable cost. In this case, the total user price would be EI, the toll would be equal to EI minus $sravc_A(q_A)$, the subsidy per trip would be KE, and the total (hourly) subsidy to the firm or agency would be equal to the product of KE and q_A. Just to place this discussion on more realistic grounds, it is likely that certain, though not many, low use and high fixed-cost turnpike and bridge authorities (e.g., perhaps the Massachusetts Turnpike Extension) find themselves in this increasing returns to scale situation and are required (because of commitments to bondholders) to price so as to cover total costs, thus causing the public at large to forego the extra net benefits accruing from a lower toll and higher use. In such instances, the local, state, or federal governments would do well to consider a subsidy (assuming, of course, that the authority would adopt marginal cost pricing).

The short-run facility A cost and D′D′ demand relations shown in Figure 7 are probably more typical or representative of present-day conditions for public highways in many dense urban core areas and thus can be used to focus attention more generally on the pricing and investment policy questions. Also, the short-run average variable cost curve for facility A can be regarded as the price function now being faced by travelers. As a result of these assumptions and conditions, use of and congestion on facility A is high, with an equilibrium flow of q_M and a total user price of MN. Clearly, this pricing policy and the resultant flow level cause serious short-run economic inefficiencies because some of the trip-makers (those represented by the demand function between flow q_p and flow q_M) will have marginal benefits that are less than the marginal costs attendant with an increase in hourly flow rate from q_p to q_M. With equal clarity it is evident that considerable long-run economic inefficiencies also result because for these conditions (i.e., facility A and demand D′D′) capacity is in short supply and grossly underexpanded. For this case and the relations shown in Figure 7, expansion to the level of facility C would bring about the following:

1. More trip-making would be permitted and thus total travel benefits would increase.
2. Total (fixed and variable) travel and facility costs would increase with expansion, but to a lesser extent than would the travel benefits. Net benefits would thus increase.
3. The price of travel for an individual trip-maker would decrease, whether the present-day user tax plus short-run variable cost pricing policy were to be continued or marginal cost pricing were to be adopted.
4. Congestion would be markedly reduced, even though the (hourly) volume rate would be increased.

At this point it is worth pointing out an anomaly that can result from considering only the effects of pricing policy changes rather than those of pricing and investment changes. (Again, let us assume that facility A is presently in existence and that the D′D′ demand curve is representative of the market for travel.) On the one hand, if the present pricing policy and its price function can be typified by the short-run average variable cost curve and if one restricts his attention to the efficiencies stemming from a switch to short-run marginal cost pricing and regards facility expansion as impossible for whatever reasons, the result will be to increase the total price of a trip from MN to PQ and to reduce the (hourly) volume rate from q_M to q_p. On the other hand, if both pricing and investment (or expansion) policy changes were to be adopted, thus switching to marginal cost pricing and expanding the capacity level to that of facility C, opposite long-run effects would result; after expansion, the trip price would be reduced from MN to FJ and (hourly) volume rate would be increased from q_M to q_C. Obviously, during the expansion period, prices—if adjusted to marginal cost—would fluctuate considerably. In the early years before new capacity was available, congestion, and thus trip price, would be high and flow would be reduced considerably (from that now witnessed with short-run average variable cost pricing). Later, after new capacity was made available and congestion dropped, the price would fall markedly and flow would increase.

The price fluctuations noted and the resultant shifts in trip-making (to other modes, to other routes, to other times of day, or to less trip-making) could, of course, cause some considerable anxieties for the traveling public as well as the business and employment groups they are dealing with. Among the numerous arguments against price fluctuation, particularly where the differences are large and when facilities have been

seriously underexpanded, there are two worth noting. First, it should be recognized that certain individuals have taken jobs and businesses have established locations based on many factors including an expectation of the continuation of existing highway pricing policies. Given a switch in pricing policy, many of these individuals or firms might find themselves in untenable economic circumstances even though they were not (or only partially) responsible for the bad predictions about policy changes. Thus, it seems wise to ask whether it is fair for them to suffer the costs stemming from the switch in pricing policy (10). Second, Boiteux (11), among others, has argued the desirability of maintaining steady rates over periods of changing demand and expansion and of setting a constant price equivalent to one that would result if the facility capacity were always in perfect adjustment. This would seem particularly important when facilities have been seriously underexpanded.

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User Benefits in Economic Analysis of Metropolitan Freeway Construction

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An extensive two-phase study of highway user benefits resulting from the operation of the Seattle Freeway is analyzed for the purpose of simplifying the data requirements and methods of calculation. Results of the detailed study of benefits indicate that travel time savings and accident reduction benefits are the principal components of urban highway user benefits. The basic form of the travel time savings calculation is analyzed. Use is made of the minimum travel time ratio (mttr) to evaluate travel time savings. It is hypothesized that the relationships between the mttr and highway and traffic characteristics will facilitate its estimation. Calculations using these ratios in conjunction with coarse time-of-day subgroupings and a truck factor, to account for the disproportionate travel time benefits enjoyed by commercial vehicles, produce benefits in substantial agreement with the results of multivehicle analysis. An analogous method of accident reduction benefit calculation is proposed. A reliable method of freeway and arterial accident cost estimation is used. A simplified procedure of benefit calculation is presented and tested against the results of previous analysis. Agreement within 2 percent is achieved. The sensitivity of the calculated travel time and accident reduction benefit to errors in the component factors is examined. With one exception, the results are not overly dependent on individual estimates. The results indicate that a simplified method can be used to estimate freeway user benefits in urban areas. A minimization of the data requirements for analysis purposes should facilitate future benefit calculation. Supplementary research of a limited nature may be necessary in the extension of these methods.

•AN EXTENSIVE before-and-after study of three components of highway user benefits was conducted in the Seattle area. The first phase of the study was carried out on four principal components of the 1962 arterial street system. The second phase of the investigation was implemented in 1968 when the entire 16.6-mile length of the Seattle Freeway was open to traffic and local traffic patterns had been allowed to readjust and stabilize (1).

The travel time benefit was definitely the easiest to measure and the hardest to evaluate. Using standard techniques of travel time and delay measurements (2), data were gathered on over 2,000 test runs on the arterial and freeway routes. Because of the significant reductions in arterial traffic volumes, peak period travel times on the arterial routes have decreased by up to 25 percent. The freeway provides a larger benefit by reducing travel times up to 60 percent in comparison to the arterials. Somewhat smaller travel time benefit levels are observed during the off-peak periods (1).

The difficulties normally associated with accurate fuel-consumption measurements for benefit analysis purposes are offset in part by the ease with which the results are

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evaluated monetarily. Fuel consumption was measured concurrently with travel time, using a specially designed fuel meter (3). Although the five types of test vehicles demonstrated different fuel consumption characteristics, analysis indicated that the primary recipients of this benefit component were the standard sedan and the large diesel tractor-trailer (3S2). Arterial fuel-consumption characteristics are dominated by the results for the van-type truck, which consumed more fuel while operating at the lower volume conditions in 1968. The resultant negative fuel benefit for this type of vehicle perhaps reflects a benefit trade-off involving increased vehicular service capabilities (1). The monetary value of the net fuel benefit is equivalent to 1 percent of the travel time benefit.

A third benefit element, resulting from the differential accident rates and costs for arterials and freeways, was evaluated and found to be significant in comparison to the other user benefits (1). Using actual property damage costs for a systematic sample of accidents, a mathematical model was developed relating reported and actual costs. Based on work by others, adjustments were made for injury and fatality costs. Although freeway accidents were found to cost 25 percent more than arterial accidents, the large differential in accident rates results in a net freeway user benefit.

The methodology and results of the exacting fuel and travel time surveys involving five test vehicles operating on five test routes are reported elsewhere (4). The scope and results of the unique accident reduction benefit analysis are reported by Matteson (5). This paper concerns itself with the utilization of the basic procedures and results of these studies to develop a simplified methodology of urban highway user benefit analysis.

THE 1968 BENEFITS

The 1968 user benefits, based on the previously mentioned analysis, total $35.6 million and are definitely in excess of the user benefits projected prior to freeway construction. The higher level of benefits is due principally to the large volume of induced traffic using the freeway. Analysis indicated that the total freeway traffic, which exceeds even the most liberal preconstruction estimates, is composed of nearly equal elements of diverted and generated traffic.

The component user benefits, calculated on the basis of finely stratified subgroupings of the data with recognition given to the differential level of benefits for diverted and generated traffic, are summarized in Table 1. The relative monetary importance of the benefits indicates that the accident reduction benefit may be more important than previously thought. The comparatively small value of savings in fuel consumption is in accordance with the results of other studies (6). Time savings provide the largest benefit component, although the monetary value of this benefit is directly related to the assigned unit value of time. Under an assumption of uniform annual benefits, it is seen that the benefit exceeds the net annual highway cost, thus providing a favorable benefit ratio. Giving consideration to the different lifetimes of the highway cost elements, the rate of return is approximately 9 percent.

TABLE 1

SUMMARY OF 1968 BENEFITS IN THOUSANDS OF DOLLARS

Category	Freeway		Arterial
Travel time			
Passenger vehicles	24,785		2,841
Commercial vehicles	3,222		-111[a]
Fuel consumption			
Passenger vehicles	390		0
Commercial vehicles	46		-69[a]
Total accident reduction	4,570		—[b]
Total benefit		35,674	
Net annual highway cost	24,800		

[a]The negative benefits for commercial vehicles operating on the arterials are explained in detail in another report (4).
[b]No arterial accident benefit was observed in this study.

The benefit summary appears in such a simple form that the costs involved in the economic analysis are not readily appreciated. In actuality, the cost of this investigation exceeded $75,000, with data collection and analysis costs being nearly equal. Recognizing that staff and financial limitations preclude frequent studies of this nature, it is logical to reexamine the structure of the investigation to determine if approximation techniques might be used to simplify the analysis while retaining the integrity of the study.

A TRAVEL TIME BENEFIT MODEL

The travel time savings benefit, being monetarily the largest of the highway user benefits resulting from this improvement, is easily examined on a theoretical basis. In essence, the basic form of a travel time savings calculation can be expressed as follows:

$$B = (T)\ (\Delta t)\ (C) \tag{1}$$

where

B = user travel time benefit, dollars per year;
T = annual route travel, person-trips per year;
Δt = unit travel time savings, hours per trip; and
C = cost of time, dollars per person-hour.

The factor T is, of course, composed of several variables, normally assumed to be independent. Vehicle occupancy, average traffic volumes (ADT), and a factor converting from daily to annual volumes (in general, not equal to 365 in an urban area) are used to determine T. In the typical case, where traffic volumes are not uniform over the route length, volumes must be weighted over several sections of roadway. Thus, T is evaluated using the following equation:

$$T = (O)\ (D)\ (L)^{-1} \sum_{i=1}^{n} L_i V_i \tag{2}$$

where

O = vehicle occupancy, person-trips per vehicle;
D = volume conversion factor, days per year;
L = total route length, miles;
L_i = length of section i, miles; and
V_i = traffic volume on section i, vehicles per day.

Based on existing or easily obtained information, this value is readily determined. Projections of future travel can normally be made using existing techniques and localized assumptions. In most cases, future travel estimates have been based on historical traffic growth, projected population and vehicle registration trends, and anticipated land use development.

The unit travel time savings represents the difference in vehicular operating times between the existing and the proposed conditions. Because travel time in urban areas is definitely a function of traffic volumes, T and Δt are not independent. Peak period congestion mirrors this dependency. The fact that peak and off-peak period travel times differ has been well established. However, the extent of time-of-day subgroupings necessary to evaluate this difference and to provide reliable analysis has not been researched in detail. Directional time-of-day subgroupings have been used by several investigators to stratify the data.

Care must normally be exercised in this subdivision, because in urban areas of moderate size neither the peak hour nor the peak period volumes (generally 2 hours) adequately describe the amount of travel occurring under higher volume and lower speed conditions. The impact of heavily directional peak period traffic volumes, which in some cases requires the use of reversible lanes or roadways, further complicates the problem.

In the Seattle area, approximately 20 percent of the travel occurs under peak volume conditions. This relationship holds true for all test routes, despite the fact that the time of the peak hour is not uniform among the several test routes, or even at different points along the same test route. It was theorized that this percentage might form the basis for a simplified time subdivision structure, recognizing the two elements of peak

and off-peak travel. Adjusting Eq. 1 under the localized assumption that 20 percent of the travel occurs during the peak period, we have

$$B = (T)\ (C)\ (0.2\ \Delta t_1 + 0.8\ \Delta t_2) \tag{3}$$

where

Δt_1 = peak period unit time savings, and
Δt_2 = off-peak period unit time savings.

Of itself Eq. 3 is not a radical departure from current practice. However, it does isolate in a simple format the specific data requirements. Normally, the difficulty in evaluating the travel time benefit results from an inability to evaluate the unit time savings. In the truly comprehensive studies (4, 6), a fleet of test vehicles is operated for several days on specific test routes to gather the needed data. If care is exercised to determine exactly what was measured, this method can be considered valid.

In the course of evaluating the merits of alternative estimators, the concept of a minimum travel time ratio (mttr) was investigated. As hypothesized, this ratio relates the minimum route travel time (t), defined as the time required to negotiate the route at the posted speed limit, to the average route travel time for a typical passenger vehicle. Assuming that the speed limits have been established in accordance with accepted traffic engineering standards (7), the upper limit of the ratio is unity.

Recognizing that there are inherent differences among arterials with respect to speed limits, access control, and the like, the congruity of the values for the mttr for the two arterial test routes enjoying significant time savings was investigated. Only slight interroute differences were observed, and a set of mean values was calculated. These values are as follows:

Route	Year	Peak Hour	Off-Peak Hour
Freeway	1968	0.80	0.94
Arterial	1968	0.78	0.86
Arterial	1962	0.67	0.80

Recalling that the mttr has a maximum value of one, improvements between 1962 and 1968 of 33 and 30 percent are observed for the arterial peak and off-peak hours respectively. The value of 0.80 for the freeway during the peak hour represents a condition of moderate congestion, whereas the off-peak value of 0.94 is associated with a freeway level of service B, i.e., stable flow with operation, speeds beginning to be restricted somewhat by traffic conditions (8).

The actual travel time is easily estimated when the mttr has been established. The quotient of the minimum route travel time and the mttr provides the actual travel time. The value of this method is that the mttr is related (in a manner not yet defined) to several observable variables, such as design speed, volume/capacity ratios, access control, and signal progression. Basing the mttr on data from a typical passenger vehicle, which is an acceptable procedure because no significant difference in travel times could be found among the compact sedan, the standard sedan, and the pickup truck (1), the number of required test vehicles is reduced.

The value of C, the cost of time, has been the subject of numerous studies. In a companion analysis (4), a value of \$2.50 per person-hour is used. In arriving at this cost, recognition was given to the generally higher value of commuter (9, 10) and business time and the normally lower values of time associated with other trip purposes. It must be noted that commercial vehicle unit time costs are typically in the range of \$4.00 to \$8.00 per vehicle hour (11, Table 35), reflecting the values of driver wages and other associated costs. In the Seattle study, it was found that commercial vehicles enjoyed 12 percent of the annual time savings benefit, although they constitute only 5.6 percent of the traffic (4). To account for this fact, a truck factor Z was defined as

$$Z = \frac{\text{(percent passenger vehicles) (total time benefit, dollars)}}{\text{(passenger vehicle time benefit, dollars)}} \tag{4}$$

Equation 3 can be modified, using the theory of the mttr to evaluate the unit time savings and the truck factor, to account for the disproportionate benefit to commercial vehicles. The following equation is obtained for individual arterial travel time benefits:

$$B = (T)\,(C)\,(Z)\left[0.2\left(\frac{t}{m_{11}} - \frac{t}{m_{12}}\right) + 0.8\left(\frac{t}{m_{21}} - \frac{t}{m_{22}}\right)\right] \tag{5}$$

where

m_{11} = peak hour mttr for existing arterial,
m_{12} = peak hour mttr for relieved arterial,
m_{21} = off-peak hour mttr for existing arterial, and
m_{22} = off-peak hour mttr for relieved arterial.

Although this equation is appropriate for arterial analysis, the form must be altered to permit evaluation of freeway user benefits. Because freeway volume is composed of both diverted and generated traffic, which are normally assumed to enjoy different levels of benefits, it is necessary to assign portions of the freeway travel to the available arterial routes, and to establish the unit benefits for the diverted and generated traffic. This may be accomplished by using a set of predicted diversion factors, $A_1, \ldots, A_i, \ldots, A_n$, where A_i is the percent of diverted freeway traffic having arterial route i as the alternate route of travel. A complementary set of factors, A_i^*, can be used to characterize the generated traffic using the freeway. These factors will be established on the basis that

$$\sum_{i=1}^{n} A_i + \sum_{i=1}^{n} A_i^* = 1 \tag{6}$$

The calculation of the freeway travel time benefit for diverted traffic requires the use of the factors A_i in conjunction with total freeway volumes. The travel time savings for diverted traffic is based on the mttr's for the projected alternatives of freeway travel and arterial travel without the existence of a freeway. The associated benefit is expressed as follows:

$$BF = (T)\,(C)\,(Z_F)\left[0.2\sum_{i=1}^{n} A_i\left(\frac{t}{m_{1i}} - \frac{t'}{m_{1F}}\right) + 0.8\sum_{i=1}^{n} A_i\left(\frac{t}{m_{2i}} - \frac{t'}{m_{2F}}\right)\right] \tag{7}$$

where

t' = minimum freeway travel time,
m_{1i}, m_{2i} = peak and off-peak hour mttr for arterial i,
m_{1F}, m_{2F} = peak and off-peak hour mttr for freeway, and
Z_F = freeway truck factor (not necessarily equal to Z).

Using the set of diversion factors A_i^* and the appropriate values for the mttr, the benefit for generated traffic is calculated in an analogous manner. The actual benefit calculations for both the arterial and freeway users are straightforward once the parameters have been estimated. The truck factor, which in theory is based on the final results of a multivehicle study, is the only exception to the basic data requirements of this method. Based on the results of an analysis, the truck factor was found to be unity for the arterials and 1.07 for the freeway. Even though these values are probably unique to this study, they should provide a guide for localized estimations.

The reliability of Eqs. 5 and 7 for estimating user time savings benefits was tested by utilizing only the basic data (i.e., traffic volumes, passenger vehicle travel time)

from the detailed study, and comparing the results with the established travel time benefits summarized in Table 1. Using Eq. 5, the arterial travel time benefit was found to differ from the results of the previous multivehicle analysis by less than 1 percent. The freeway user benefit, based on equations for generated and diverted traffic characterized by Eq. 7, was virtually identical with the sum of the freeway travel time benefits for passenger and commercial vehicles given in Table 1.

The degree of reproducibility of this component of user benefits is unexpected. Interpreted within their area of relevance, Eqs. 5 and 7 indicate that refinements in traditional methods of analysis can be made to account for the nonuniform distribution of benefits among the several types of vehicles. In addition, it appears that extensive analysis of directional peak and off-peak hour travel for the purpose of maintaining accurate estimation levels may not always be necessary.

In the general case, knowledge of the relationship between the value of mttr and the several associated driver and highway characteristics will limit the applicability of these equations. A small but continuing localized study and analysis of the mttr should provide the best guide in predicting its value.

AN ACCIDENT REDUCTION MODEL

Very low freeway accident rates (2.0-3.0 per million vehicle-miles) (12) compared to the universally higher rates on arterials will generally provide a net freeway user benefit. Although some researchers have noted a direct relationship between traffic volumes and accident rates, a statistically significant reduction of arterial accident rates resulting from the diversion of arterial traffic to the freeway was not observed in the Seattle area. Based on the research reported by Matteson (5), it is possible to discuss this benefit only as it occurs to freeway users.

The calculation of an accident reduction benefit must consider the amount of travel, the probability of an accident, and the cost of an accident. In a basic form, the calculation is expressed as follows:

$$AB = (V)\,(L)\,(AC) \tag{8}$$

where

AB = user accident reduction benefit, dollars per year;
V = annual route traffic volume, vehicles per year;
L = route length, miles; and
AC = unit savings in accident cost, dollars per vehicle-mile.

The route length, L, is easily determined, while the annual volume, V, is calculated in a manner similar to Eq. 2, (i.e., $V = T/O$). However, many analyses cannot complete this calculation for lack of a unit value of accident costs.

Matteson describes a reliable method of adjusting property damage costs as estimated by the driver or the enforcement officer to predict actual accident costs (5). Based on a detailed study of a 10 percent sample of Seattle freeway accidents, these adjustment equations are

$$C' = (1.15802)D^{0.997898} \tag{9}$$

$$r_D = 0.946$$

$$C' = (0.77464)E^{1.062966} \tag{10}$$

$$r_E = 0.892$$

where

C' = actual property damage cost per vehicle,
D = drivers' property damage estimate,
E = enforcement officers' property damage estimate, and
r_D, r_E = correlation coefficients.

Although these equations provide good estimates of accident cost, they must be used prudently because of the limitations of the basic research. Because they evaluate only property damage cost per vehicle, the number of vehicles involved per accident must be considered. For both the freeway and the arterials, it was found that there were 1.93 vehicles per accident (1). A separate factor must be used to account for injury and fatality costs. Based on the results of accident cost studies by Drake and Kraft (13) and Matteson (5), and adjusting downward for the economic importance of loss of future earnings, it was found that injury and fatality costs constitute 61 percent of total accident costs. Incorporating these two factors, the average Seattle freeway accident cost is \$1,467, whereas the arterial accident cost is \$1,172.

The unit savings in accident cost resulting from a comparison of the Seattle Freeway with arterial i is

$$AC = 10^{-6} \left(\$1{,}172\ R_i - \$1{,}467\ R_F\right) \tag{11}$$

where

R_i = arterial accident rate, accidents per million vehicle-miles; and
R_F = freeway accident rate, accidents per million vehicle-miles.

In the most general case, the diverted and generated traffic will enjoy different unit savings, equal at the time of their generation or diversion to the value of AC given by Eq. 11. When past arterial accident rates vary slightly from year to year, an average accident rate can be used. For projection purposes, a freeway accident rate can be established by comparison with local freeways having similar design and operational characteristics.

Incorporating the previously defined diversion factors, A_i and A_i^*, to account for the percent of generated and diverted freeway traffic that has arterial i as the alternate route of travel, Eq. 8 for diverted traffic can be expressed as

$$AB = (V)\ (L)\ (10^{-6}) \sum A_i \left(\$1{,}172\ R_i - \$1{,}467\ R_F\right) \tag{12}$$

A similar equation can be established for generated traffic. In deriving these equations, uniformity of average accident costs among the arterials was assumed. If there is reason to believe that this may not be the case, the equation is easily modified, although the analysis is consequently lengthened.

The verification of these equations, using average values of R_i, resulted in an annual user benefit of \$4.49 million, approximately 2 percent less than the benefit given in Table 1. The difference is primarily attributed to Matteson's use of more refined techniques regarding the source of freeway traffic (5).

IMPORTANCE OF THE FUEL CONSUMPTION BENEFIT

Table 1 gives an indication that, based on detailed analysis, the savings in fuel consumption resulting from freeway operation is comparatively small. In monetary terms, this benefit is approximately 1 percent of the travel time savings and 8 percent of the accident reduction benefit. Because the fuel savings is the same order of magnitude as the error resulting from the benefit-prediction equations, no attempt is made to develop an equation for estimating these savings. The relative impact of these three types of user benefits should be noted in future analysis of urban facilities.

SENSITIVITY TO INCORRECT COMPONENT ESTIMATION

For evaluation of the simplified benefit equations, it is necessary to determine the values of a limited number of variables. In the general case, the existing conditions (volumes, travel time ratios, and accident rates) can be measured. The future values for these components must be estimated for a specific locale using available techniques. It is important that the economist note the sensitivity of the resultant benefit to errors in such estimates.

In some cases the dependency is quite obvious. For example, the value of B obtained from Eq. 5 will change in direct relationship to changes in T, C, or Z. Thus, if the travel T′ exceeds the estimated travel T by 10 percent, the actual and estimated benefits will also differ by 10 percent.

However, a direct relationship does not exist between B and the travel time ratios. Referring to Eq. 5, the partial derivative of B with respect to m_{12} is determined:

$$\frac{\delta B}{\delta m_{12}} = (T)\,(C)\,(Z)\left[0.2\left(\frac{t}{m_{12}^{2}}\right)\right] \tag{13}$$

From Eq. 13, it is clear that

$$\delta B = B(\delta m_{12})\,(0.2)\left(\frac{t}{m_{12}^{2}}\right)\left[0.2\left(\frac{t}{m_{11}} - \frac{t}{m_{12}}\right) + 0.8\left(\frac{t}{m_{21}} - \frac{t}{m_{22}}\right)\right]^{-1} \tag{14}$$

Equation 14 indicates that the user benefit is quite sensitive to changes in the travel time ratio, and, in general, $\delta B > (B)\,(\delta m_{12})$. For the specific case studied, a 2.5 percent reduction in m_{12} (changing 0.78 to 0.76) results in a 6.5 percent reduction in the user benefit. A similar relationship holds for the freeway user travel time benefit equation. As a result, it is important that the mttr be carefully estimated.

Because the accident benefit is related to the portions of traffic that might have used the available arterial routes, an error in the estimation of a specific value of R_i affects the calculated benefit in relation to the associated value of A_i. An error in estimating R_F is normally of comparatively minor importance because, in general, $R_i > 2R_F$. For the data previously analyzed, a 12.0 percent error in the estimate of R_F (assuming R = 2.5 instead of the correct value, 2.81) results in a benefit that is incorrect by approximately 3.0 percent.

CONCLUSIONS

The economic analysis of urban highway facilities has traditionally been hampered by the apparent need for an extensive program of data collection. This report has shown that it is possible to duplicate the results of an extensive analysis using a simple benefit model in conjunction with several data approximations. In evaluating the travel time and accident reduction benefits, which outweigh the fuel consumption savings in the typical urban situation, a limited data-gathering program is sufficient to permit accurate benefit analysis. This analysis may not be acceptable in areas having unusual topography or a high percentage of commercial vehicles.

With respect to the travel time benefit, additional research in the specific area of the relationship of travel time ratios to the several associated variables would be quite beneficial. For accident reduction analysis, localized accident cost information is required. The magnitude of this latter benefit suggests that it is worthy of consideration in urban freeway analysis.

It is hoped that the simplified benefit evaluation models that have been developed and presented in this paper may, within the domain of their applicability, serve as a guide for future user benefit analysis in urban areas.

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Vehicle Characteristics of Fuel and Travel Time on Urban Arterials and Freeways

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This report evaluates the impact that urban freeways have on vehicle operating characteristics of travel time and fuel consumption. The study is unique in that seldom has a before-and-after study been conducted as comprehensively or over as long a period as this project. The "before" portion was conducted in 1962 before any freeways were open to traffic in the Seattle area. The "after" portion was conducted in the summer of 1968, approximately 6 months after the Seattle Freeway was completely open to traffic. Travel time and fuel consumption data were collected for five classifications of vehicles operating over four parallel arterial routes as well as on the freeway. On only two of the parallel routes was there a statistically significant reduction in traffic volume with a corresponding savings in travel time. The total time savings benefit for 1968 as a result of the freeway construction was $30,737,000, or about 12 percent of the construction costs. The evaluation of the fuel consumption benefit presented some difficulty. The vehicles used in the after portion were calibrated with their counterparts in the before study. Constant speed calibration does not appear to adequately represent a vehicle adjustment factor when applied on routes with variable operating speeds. Stratification of traffic volume into peak and off-peak periods was also required. In general, statistically significant savings were observed for the passenger car on two of the secondary routes but not on the major parallel route, even though a time savings was experienced. The major fuel benefits accrued to passenger cars directed from the old arterial route to the freeway. At all time periods the diesel truck experienced fuel savings on the freeway compared to its operation on the old major arterial route. Despite a small negative fuel benefit for vehicles continuing to operate on the arterial routes, the total system fuel savings is $366,000 for 1968. Approximately 25 percent of this benefit is attributable to diesel-powered vehicles.

•THE MEASUREMENT of vehicle operating characteristics of travel time and fuel consumption is certainly not a new technique to the engineering profession. However, the application of the most practical methods and equipment to network or corridor travel to evaluate the impact before and after freeways are constructed in an area is not generally researched. In 1962 the University of Washington entered into a research contract with the Washington Department of Highways and the U.S. Bureau of Public Roads to perform the "before" portion of such a study in the Seattle area. At that time, sections of the Seattle Freeway were under construction but were not open to traffic. The "after" portion of the study was conducted in the summer of 1968 when the Seattle

Paper sponsored by Committee on Vehicle Characteristics and presented at the 49th Annual Meeting.

Freeway was open to traffic through and beyond the city limits of Seattle. The impact evaluation considered travel time, fuel consumption, and accidents on four parallel arterial routes in the north-south corridor.

TEST ROUTES

The routes, shown in Figure 1, were subdivided into sections for comparison of travel time and fuel consumption over shorter distances. Travel time sections average about ¾ mile in length, whereas fuel sections, which require a sufficient distance to

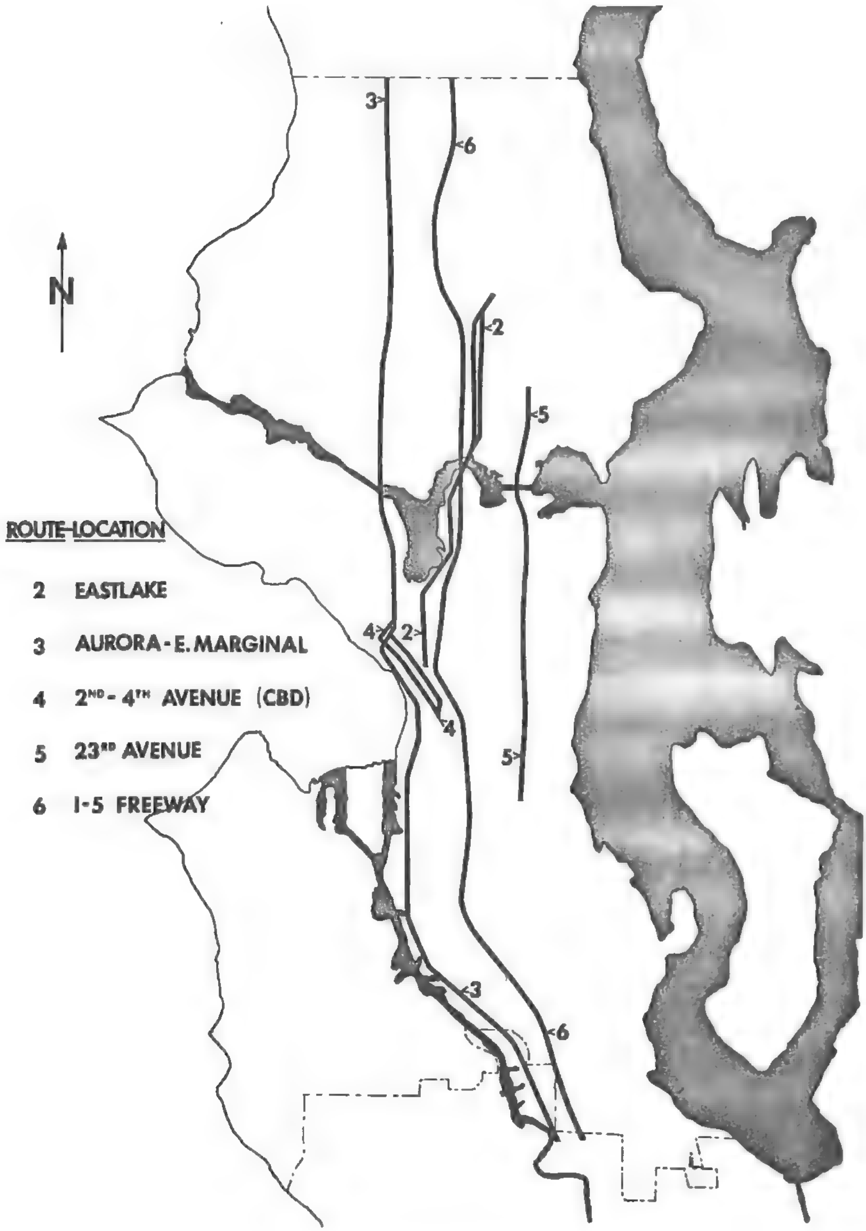

Figure 1. Seattle area test routes.

provide an adequate quantity of fuel for reliable fuel consumption measurements, are about 2 miles in length.

One additional test section, used for vehicle-calibration purposes, was located approximately 11 miles south of Seattle on Interstate 5. This route was used to measure fuel consumption at several constant speeds for each of the five test vehicles. A summary description is given in the following.

Route 2

Test Route 2, a Seattle arterial that closely parallels the route of the freeway, is a section of State Route 522. The route begins at Fairview Ave. and Denny Way, crosses under the freeway just south of the Lake Washington Ship Canal, and extends northward to the terminal point at 15th Ave. N.E. and Lake City Way (formerly Bothell Way). The portion of the route north of the canal is a one-way couplet with 11th and 12th Avenues N.E. northbound and Roosevelt Way N.E. southbound.

Route 3

Old US-99, formerly the major north-south route through Seattle, is designated as Route 3. The route begins at the Duwamish junction and extends northward on E. Marginal Way, the Alaskan Way viaduct, the Battery St. tunnel, and Aurora Ave. to the north city limits of Seattle at N. 145th St. The route is approximately 17 miles in length, and is between 1 and 2 miles west of the Seattle Freeway. The traffic conditions near the south end, from the Duwamish junction to the Spokane St. overcrossing, are strongly influenced by traffic generated by the Boeing Company.

Route 4

Test Route 4 is the shortest of the routes. It includes a portion of the old US-99 business route, and consists of sections of 2nd Ave. and 4th Ave. forming a one-way couplet in the Seattle central business district. Although it was anticipated that the freeway would have an influence on the traffic operations on this route, it must be noted that many other variables can similarly affect travel in the CBD.

Route 5

Route 5 extends northerly from the intersection of 23rd Ave. and Rainier Ave. S. to the intersection of 25th Ave. N.E. at E. 55th St. Part of this route coincides with State Route 513. It was expected that the freeway would not significantly affect this route, but that it would be relieved by the construction of the proposed R. H. Thomson Expressway.

Route 6

The Seattle Freeway, Interstate 5, from E. Marginal Way to N. E. 145th St. was designated as Test Route 6. This facility has a minimum of six lanes, and the portion from Yesler St. to N. 110th St. has an additional reversible roadway. The first section of this route opened to the public was the Freeway Bridge over the Lake Washington Ship Canal (December 18, 1962). The main roadway was completed with the removal of the southbound detour between the Dearborn and Spokane St. interchanges (August 24, 1967).

Route 7

A 12.8-mile section of Interstate 5 between the Port of Tacoma Road (Pierce County) and S. 240th St. (King County) was used for vehicle calibration, and is referred to as Test Route 7. This route has not been redesigned or modified since the 1962 study.

TEST VEHICLES

A group of five test vehicles, chosen initially in 1962, was selected to be representative of the majority of vehicles in use on the highways. The test vehicles included a

compact sedan, a standard 4-door sedan, a pickup truck, a single-unit truck with dual rear tires, and a diesel tractor-trailer unit (3S2). The details on vehicle specifications are given in Table 1. There are minor differences between the test vehicles used in the 1962 and the 1968 study. For the most part, these differences reflect an increase in horsepower (about 10 percent for the passenger vehicles, 30 percent for vehicle 50) resulting from improvements in engine design and components.

TEST EQUIPMENT

In a study and analysis of vehicle operating characteristics, it is necessary to gather accurate data on fuel consumption, travel time, distance, and traffic volumes. The basic test equipment used in this study is similar to that used in the before study.

Fuel Metering Devices

Two different devices are available for the accurate measurement of fuel consumption. A fuel meter, model FM 200, developed by the University of Washington was used on the passenger cars. This meter is designed to measure fuel over a broad fuel flow range, by counting the number of times that two small chambers within the meter have been filled with fuel and then emptied. The chamber volume is approximately 2.5 ml. A correction must be made for the volumetric change in fuel with a change in temperature. At each fuel checkpoint, the observer recorded the number of counts on the FM 201 counter assembly, which is located in the passenger compartment, and at the end of each test turn the fuel temperature registered on an immersion-type dial gage was recorded.

Because only one FM 200 was available for use in this study, and because concurrent operation of the cars and trucks was desired, it was necessary to use burette boards to measure truck fuel consumption. The burettes are read directly in milliliters of fuel used, although corrections must be made for fuel temperature. The fuel metering devices are discussed in detail in a previous report (1).

Time Measurement

Typical laboratory stopwatches, measuring time in increments of $^1/_{100}$ minute, were used to measure travel and delay time. Standard accuracy tests were performed on the

TABLE 1
1968 TEST VEHICLE SPECIFICATIONS

Category	Vehicle Number				
	10	20	30	40	50
Axle class	2	2	2	3S2	SU2D
Year of manufacture	1961	1967	1965	1968	1968
Make	Falcon	Chevrolet	Chevrolet	White	Ford
Body type	2-door sedan	4-door sedan	Pickup	Tractor-trailer	Van truck
Wheelbase	110 in.	119 in.	127 in.	46 ft 0 in.	12 ft 9 in.
Overall length	181 in.	213 in.	206 in.	54 ft 0 in.	25 ft 0 in.
Fuel	Gasoline	Gasoline	Gasoline	Diesel	Gasoline
Cylinders	6	8	6	6	8
Displacement, cu. in.	170	283	250	743	361
Net horsepower at rpm	110/4400	195/4800	155/4200	220/2100	210/4000
Rear axles ratio: 1	3.50	3.08	4.11	4.88	7.20
Transmission type	Automatic	Automatic	Standard	Standard	Standard
Ratio: 1 (gear/ratio)	Low/1.75 High/1.00 Rev./1.50	Low/1.82 High/1.00 Rev./1.82	1st/N. A.[a] 2nd/N. A.[a] High/1.00	9th/1.35 10th/1.17 11th/1.00 12th/0.87 Rev./12.50	3rd/2.10 4th/1.17 5th/1.00 Rev./5.89
Tire size	6.50 × 13	8.25 × 14	7.75 × 15	10.00 × 22	9.00 × 20
Gross vehicle weight[b]	2,820	4,100	4,500	47,200	13,300

[a]N.A. = not applicable.
[b]Includes weight of driver, observer, and test equipment. Vehicles 30, 40, and 50 were loaded with additional weight to simulate typical driving conditions.

watches prior to the testing program. Side start watches were used to measure delay time for each section. Accumulated delay time and cause of delay were recorded by the observer. The driver measured total elapsed test route time with a stopwatch affixed to the center of the steering wheel.

Distance Measurements

Accurate distance measurements on all test sections were made using a calibrated survey odometer. The meter recorded to $\frac{1}{1000}$ mile. Route distances were measured three times, both northbound and southbound. Checkpoint locations were generally established at the centerlines of intersecting streets.

Traffic Volumes

An extensive traffic volume counting program was undertaken with the cooperation of the Washington Department of Highways and the Seattle Traffic Engineering Department. Counts were taken at one or more locations on each test route while the test vehicles were making runs. A catalog of all volume counts taken on these routes since 1965 was assembled. Records from several permanent count locations in the Seattle area were obtained for the purpose of establishing traffic volume variations.

ANALYSIS OF TRAVEL TIME SAVINGS

During the course of the after study, approximately 1,000 test runs were made. A similar number of runs were made during the before study, although in 1962 there was one less test route. Computer processing of the field data greatly facilitated the handling of these large amounts of information.

During the preliminary analysis of the 1968 data, test runs were separated according to test route, direction of travel, and type of vehicle. Unweighted averages were established for the categories of overall and running speeds, travel time and delay, and fuel consumption. Computer output from the 1962 study was in a similar format.

TRAVEL TIME DATA

One of the primary objectives of this study was to verify the effect of highway improvements in the Seattle area on vehicular travel time. It was felt that general trends in travel time changes might be noticed in an analysis of the original computer output. Several patterns were observed, but the variance of the results restricted any meaningful analysis of the data in this form.

The difficulty in establishing definite trends from the preliminary arrangement of data prompted a restructuring of the computer outputs to provide information on travel time as a function of time of day. Course time subgroupings were established as follows: morning peak hour—trips beginning between 7:15 and 8:14 a.m.; evening peak hour—trips beginning between 4:30 and 5:29 p.m.; and off-peak hour—trips beginning at all other times.

A review of the data separated according to test route, direction of travel, vehicle number, and time of day accentuated the trends of travel time reduction. Table 2 gives the results of a comparison of travel times for vehicles 2 and 20, which are similar to the majority of vehicles on

TABLE 2

TRAVEL TIME COMPARISONS STRATIFIED BY TIME OF DAY

Route	Time of Day	Travel Time in Minutes[a]			
		Northbound		Southbound	
		1962	1968	1962	1968
2	Morning peak	15.46	12.12	19.66	14.11
	Evening peak	19.53	15.15	15.15	15.12
	Off-peak	14.41	12.75	13.62	13.59
3	Morning peak	33.36	31.19	40.51	30.75
	Evening peak	47.58	34.95	29.48	31.55
	Off-peak	30.65	29.58	31.31	29.27
4	Morning peak	6.82	7.40	5.94	6.53
	Evening peak	10.52	9.24	9.04	5.78
	Off-peak	6.98	7.29	6.75	6.33
5	Morning peak	14.25	14.57	18.88	13.90
	Evening peak	18.11	15.85	15.04	16.98
	Off-peak	14.67	14.02	13.80	14.26
6	Morning peak	—[b]	16.79	—[b]	19.42
	Evening peak	—[b]	20.36	—[b]	17.22
	Off-peak	—[b]	17.93	—[b]	17.09

[a]Vehicles 2 and 20, standard sedans.
[b]The freeway route was not open to traffic in 1962.

the roadway. There are travel time reductions on all routes, although three of the subgroupings for both Routes 4 and 5 show increases in travel time between 1962 and 1968.

Despite the total of 262 test runs made by vehicle 20, when the results are divided into 30 subgroupings, as shown in Table 2, it is inevitable that some of the travel time averages will be based on a small number of runs. It is not appropriate to base final analysis on small sample average travel times. In such cases, the variance of the data is large enough to preclude statistically significant conclusions.

Because vehicles 10, 20, and 30 exhibit maneuverability characteristics of typical passenger vehicles, and because the drivers of these vehicles were given the same driving instructions, i.e., to travel at the same speed as the traffic flow, it was hypothesized that there should not be significant differences in travel times among these vehicles for specific routes, directions, and times. To test this hypothesis, it is necessary to use a test that is appropriate for small samples.

Extensive analysis of vehicle 20 travel times indicated that the data are distributed normally. With sample size as the criterion, there are two tests for analyzing the differences between averages of random samples from normal populations having equal variances. Analysis was performed on the passenger vehicle pairs of (10, 20), (10, 30), (20, 30), and the 90 percent confidence level was used in evaluating the results. No significant difference in travel times among these three vehicles was noted for comparison between the identical subgroupings of averages. Similar analysis for selected subgroupings of travel time averages for vehicles 1, 2, and 3 confirmed this hypothesis for data from the 1962 study.

For refined travel time analysis, travel time data for the passenger-type vehicles were combined. Two composite vehicles were developed: vehicle 100, representing the average of travel time data from test vehicles 1, 2, and 3; and vehicle 200, representing a similar average for vehicles 10, 20, and 30. Travel times for these vehicles are given in Table 3. The primary benefit resulting from combining these averages is that the total of 618 test runs (in 1968) provides a much larger sample and thus a broader basis for data subdivision.

With sample size as the criterion, the student "t" test was appropriate for determining the significance of differences between the travel time averages for morning and evening subgroupings, whereas the "z" test, based on the standard normal distribution, was used for analyzing differences in off-peak averages. Table 4 summarizes the travel

TABLE 3

TRAVEL TIME COMPARISONS FOR PASSENGER VEHICLES

Route	Time of Day	Travel Time in Minutes			
		Northbound		Southbound	
		1962 (100)[a]	1968 (200)[b]	1962 (100)[a]	1968 (200)[b]
2	Morning peak	15.20	12.82	18.86	14.18
	Evening peak	19.11	15.23	14.89	15.30
	Off-peak	13.85	12.89	13.42	13.41
3	Morning peak	33.72	29.82	38.65	30.09
	Evening peak	47.01	38.37	31.59	30.60
	Off-peak	31.97	29.90	31.60	29.41
4	Morning peak	6.72	7.26	6.25	6.44
	Evening peak	10.04	9.41	10.01	7.77
	Off-peak	7.13	7.27	6.83	6.53
5	Morning peak	14.02	14.22	16.20	14.03
	Evening peak	17.82	14.98	15.05	17.40
	Off-peak	13.96	13.95	13.42	14.23
6	Morning peak	—[c]	18.14	—[c]	19.50
	Evening peak	—[c]	25.96	—[c]	17.89
	Off-peak	—[c]	17.76	—[c]	17.29

[a]Composite vehicle 100.
[b]Composite vehicle 200.
[c]The freeway route was not open to traffic in 1962.

TABLE 4

TRAVEL TIME SAVINGS, 1968 VERSUS 1962, FOR ARTERIAL ROUTES ONLY

Route	Time of Day	Time Savings for Composite Passenger Vehicles 100 and 200			
		Northbound		Southbound	
		Minutes	Significance (percent)	Minutes	Significance (percent)
2	Morning peak	2.38	99.5	4.68	99.5
	Evening peak	3.88	99.5	—[a]	
	Off-peak	0.96	99.9	—[a]	
3	Morning peak	3.90	97.5	8.56	99.5
	Evening peak	8.64	99.0	—[a]	
	Off-peak	2.07	99.9	2.19	99.9
4	Morning peak	—[a]		—[a]	
	Evening peak	—[a]		2.24	95.0
	Off-peak	—[a]		0.30	97.5
5	Morning peak	—[a]		2.17	95.0
	Evening peak	2.84	99.0	-2.35[b]	97.5
	Off-peak	—[a]		-0.81[b]	99.9

[a]Indicates subgroupings for which the difference in travel time is not significant at the 90 percent confidence level.
[b]Minus sign denotes an increase in travel time from 1962 to 1968.

time savings for the composite passenger vehicles. With the exception of Route 4, there are significant savings during the peak hours in the peak directions of traffic flow—morning peak hour southbound and evening peak hour northbound.

Increases in travel time are observed on Route 5 southbound during the evening peak and the off-peak periods. In the case of the evening peak, it seems that the increase may be due to traffic engineering changes, specifically an effective signal progression for the benefit of northbound vehicles. There is additional evidence to suggest that Route 5 has not been appreciably affected by the operation of the freeway.

Travel time analysis for the two commercial-type vehicles is inconclusive. Commercial truck operators recognize the difficulties of operation during the peak periods. As a result, these vehicles represent a small portion of peak hour traffic. For this reason, few test runs were made during the 1962 study peak periods, and thus there is no base for comparison of the two periods. However, a general trend of increasing travel time between 1962 and 1968 during the off-peak periods is observed. Using a 90 percent confidence level, there is no difference in travel times between vehicles 4 and 40 on Route 3. Within the same confidence level, there are increases in travel times between 1962 and 1968 for the van truck on Route 2 (off-peak, northbound and southbound) and on Route 3 (off-peak, northbound).

The benefits suggested by Table 4 are correlatable with respect to time with the operation of the Seattle Freeway. However, care must be exercised in interpreting the results, especially when arterial improvements may have contributed to the travel time reduction.

Travel Time Benefits of the Freeway

Without yet evaluating its total extent, the existence of travel time savings on the arterial routes has been verified. In determining the reasons for these savings, which are not due to chance, it is necessary to examine the conditions on the respective routes during the before and after periods. These include traffic volume changes, arterial street improvements, and speed limits. Because these conditions are interrelated with the operation of the freeway, it is first necessary to examine the travel time characteristics on the freeway.

Route 3 provides the most direct comparison with the Seattle Freeway. The routes differ in length by only 1 percent, and their terminal points, for trip analysis purposes, coincide. Route 3 experienced a significant traffic volume reduction after the opening of the freeway. Route 2, which closely parallels a portion of the freeway north of the CBD, also experienced a traffic volume decrease. The freeway section from the Stewart St. off-ramp to N. 85th St. is identical in length to Route 2. The terminal points of this portion of the freeway are within a mile of the terminal points for Route 2.

The traffic volume relief on Route 5 has been very slight. For travel time comparison purposes, Route 5 could be compared with the section of freeway from the Holgate St. overcrossing to N.E. 50th St. The lengths are nearly equal, but because of the spatial separation of the terminal points, the routes do not serve the same traffic demands.

With regard to test Route 4, a 1.8-mile route using a one-way couplet in the CBD, there exists a statistically significant time savings in two of the six time periods. The designation of this route as "US-99-Business" implies that it was the alternate to the parallel section of Route 3 (the Alaskan Way viaduct). The travel time on the comparable section of Route 3 is between a half and a third the travel time on Route 4, depending on the time of day. The north terminal point of Route 4 is located at its intersection with Route 3. The freeway, on the other hand, allows for faster travel (2 minutes versus 7 minutes for Route 4), but the freeway access points do not encourage its use as an alternative to Route 4. As a result, the opening of the freeway had little effect in the diversion of traffic from 2nd Ave. and 4th Ave. and, in fact, has increased the flow of cross traffic.

Table 5 summarizes the travel times for vehicles operating on the arterials in 1962 and on the freeway in 1968. For comparison with Routes 2 and 5, only portions of the freeway are used. The difference between the travel times for the arterial and the freeway represents the time saved by the motorist who elects to use only that length of

TABLE 5

TRAVEL TIME COMPARISONS, FREEWAY VERSUS ARTERIAL

Vehicles	Route	Time of Day	Travel Time in Minutes			
			Northbound		Southbound	
			Arterial	Freeway[a]	Arterial	Freeway[a]
100 and 200	2	Morning peak	15.20	5.31	18.86	6.50
		Evening peak	19.11	7.37	14.89	5.47
		Off-peak	13.85	5.40	13.42	5.40
	3	Morning peak	33.72	18.14	38.65	19.50
		Evening peak	47.01	25.96	31.59	17.89
		Off-peak	31.97	17.76	31.60	17.29
	5	Morning peak	14.02	6.63	16.20	7.47
		Evening peak	17.82	8.72	15.05	6.57
		Off-peak	13.96	6.56	13.42	6.36
4 and 40[b]	3	Morning peak	38.1	20.5	39.0	19.4
		Evening peak	44.6	25.9	(35.9)[c]	19.7
		Off-peak	38.1	20.1	35.9	19.4
5 and 50[b]	2	Morning peak	12.9	5.7	14.9	6.5
		Evening peak	18.0	9.7	15.2	5.9
		Off-peak	12.6	5.7	13.0	5.7
	3	Morning peak	32.0	19.0	35.0	20.6
		Evening peak	33.2	32.2	32.4	19.6
		Off-peak	30.5	18.9	33.0	19.4

[a]Freeway sections used for comparisons are as follows:

Route 2 (5.111 miles northbound, 5.193 miles southbound versus Route 6 from Steward St. to N. 85th (5.10 miles);
Route 3 (16.865 miles) versus Route 6 (16.630 miles);
Route 5 (5.891 miles) versus Route 6 from Holgate to NE 50th St. (5.694 miles).

[b]Truck travel time averages, based on fewer number of runs, have been rounded to tenths of minutes.
[c]Data lacking; off-peak time has been used in calculations.

freeway corresponding to the arterial route. The case of a motorist driving less than the length of the test route will be treated later using volume-averaging techniques. Considering the nature of the test routes, it is inevitable that some motorists will drive for varying distances on extensions of the test routes. Thus, a person living near the northeast city limits may choose to approach Route 2 at its northerly terminal point, or he may enter the freeway at one of the access points between the northern terminal point and the comparable point on Route 2. As a result, the time differential indicated by Table 5 is the minimum time benefit enjoyed.

Statistically, the time savings are all significant, with the exception of vehicle 50 on Route 3 in the evening peak hour traveling northbound. The appreciable size of the other time savings contributes to their recognition by the motoring public and is one of the reasons for the large diversion of traffic to the freeway. Despite the apparent time savings, however, there has been no discernible transfer of traffic from Route 5 to the freeway, probably because Routes 5 and 6 actually constitute two different travel corridors.

Analysis of Traffic Volume Trends

To evaluate the importance of these improvements in travel time, it is necessary to consider the numbers of persons receiving the benefit of the time savings. A problem of this nature is straightforward in the case where the alternate route is abandoned in favor of the new improved route. Unfortunately, this is not the case with the Seattle Freeway. Instead, existing freeway traffic must be viewed as the sum of three basic components: traffic diverted from the arterial routes, traffic resulting from normal growth, and induced traffic, which is not due to normal growth but is attributable to corridor improvements (2). The tremendous impact of this last factor is verified by the fact that, on northern portions of the freeway, traffic volumes in 1967 exceeded the forecast volumes for the design year (1975) by 33 percent.

For volume analysis purposes, Seattle is fortunate to be divided by a natural screenline, the Lake Washington Ship Canal. The canal, connecting Puget Sound and Lake Washington, is crossed by five arterial bridges (24 lanes) and the Freeway Bridge (8 lanes plus 4 reversible lanes). The traffic volumes on these bridges are given in Table 6. The traffic growth rate appears to be small during the pre-freeway years. The only other significant change prior to 1963 is the apparent transfer of some traffic from the Fremont Bridge to the Ballard Bridge in 1962 as a result of arterial improvements on the approaches to the latter bridge.

By 1962, the screenline bridge capacity was being exceeded, with the morning and evening peak periods extending longer than an hour. Some traffic was being diverted to I-405 on the east side of Lake Washington. The heavy directional flow of traffic during the peak periods required the use of reversible lanes (4/2) on the Aurora Bridge as a stop-gap measure. The opening of the section of freeway from Roanoke St. north to Ravenna Blvd. (including the freeway bridge) in December 1962 provided immediate relief to the University Bridge. By 1965, the freeway had been extended southward to the area of the CBD, and volume relief was experienced on the Fremont and Aurora Ave. Bridges. Virtually no change in traffic volumes was observed on the Ballard or Montlake Bridges. The traffic volumes at the Lake Washington Ship Canal screenline are shown in Figure 2.

Using the least-squares technique on the canal screenline volume data from 1958 to 1962, the projected volume in 1968 would have been 261,000 vehicles per day. This figure assumes that arterial improvement would have provided increased capacity, or that the peak periods would be further extended. The operation of the freeway has resulted in 1968 screenline volumes of 339,000. This is 30 percent over the projected volume. Comparing the 1968 and 1962 volumes for the Fremont, Aurora, and University Bridges, it is apparent that a minimum of 60,000 crossings have been diverted to the Freeway Bridge. If the volume growth rate is applied to the 1962 volumes on these three arterial bridges, then 96,000 crossings have been diverted to the freeway. In light of the fact that some arterial traffic is generated, logic dictates that perhaps an intermediate value, 80,000, is representative of the true value of diverted traffic. The portion of the 1968 freeway volume resulting from the accelerated traffic growth is thus 73,000.

The time benefit to the diverted traffic is dependent on the arterial route that formerly carried the traffic. The induced traffic, on the other hand, enjoys a smaller benefit, which at the time of its generation is equal to the difference in travel time between the alternative arterial route and the freeway. For benefit analysis purposes, it is justifiable to assign the generated trips to the possible arterial bridges as follows: University—28,000; Fremont—7,000; and Aurora—38,000. This assignment would adjust the 1968 bridge volumes to the 1962 levels. Further simplification, again for analysis purposes, permits the combination of Fremont and University Bridge assignments,

TABLE 6

LAKE WASHINGTON SHIP CANAL SCREENLINE VOLUMES, 1958-1968

Bridge[a]	24-Hour Total Volume										
	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968
Ballard	31,500	32,500	30,500	38,923	39,458	39,102	38,212	39,929	37,805	39,266	40,300
Fremont	29,500	30,000	34,000	28,315	31,216	28,974	26,918	23,144	29,307	23,260	26,800
Aurora	74,500	81,500	82,500	82,619	79,710	78,958	73,390	54,234	52,429	44,088	45,500
University	44,500	43,000	45,000	44,015	45,630	32,753	22,513	22,513	22,186	21,515	25,600
Montlake	43,000	43,000	42,000	43,029	41,947	41,509	43,402	41,601	42,343	42,682	48,000
Subtotals	223,000	230,000	234,000	236,901	237,961	221,296	204,435	179,282	184,070	170,811	186,200
Freeway[b]	—	—	—	—	—	25,529	50,775	92,872	109,920	141,680	153,120
Total	223,000	230,000	234,000	236,901	237,961	246,825	255,210	272,154	293,990	312,491	339,320

[a]The Ballard Bridge (4 lanes) is 3.0 miles west of the freeway; the Fremont Bridge (4 lanes) is 1.4 miles west of the freeway; the Aurora Ave. Bridge (6 lanes), on Test Route 3, is 1.3 miles west of the freeway; the University Bridge (6 lanes), on Test Route 2, is immediately east of the freeway; and the Montlake Bridge (4 lanes), on Test Route 5, is 0.9 miles east of the freeway.

[b]The Freeway Bridge opened in 1962, although the final sections comprising test section 6 were not completed until 1967.

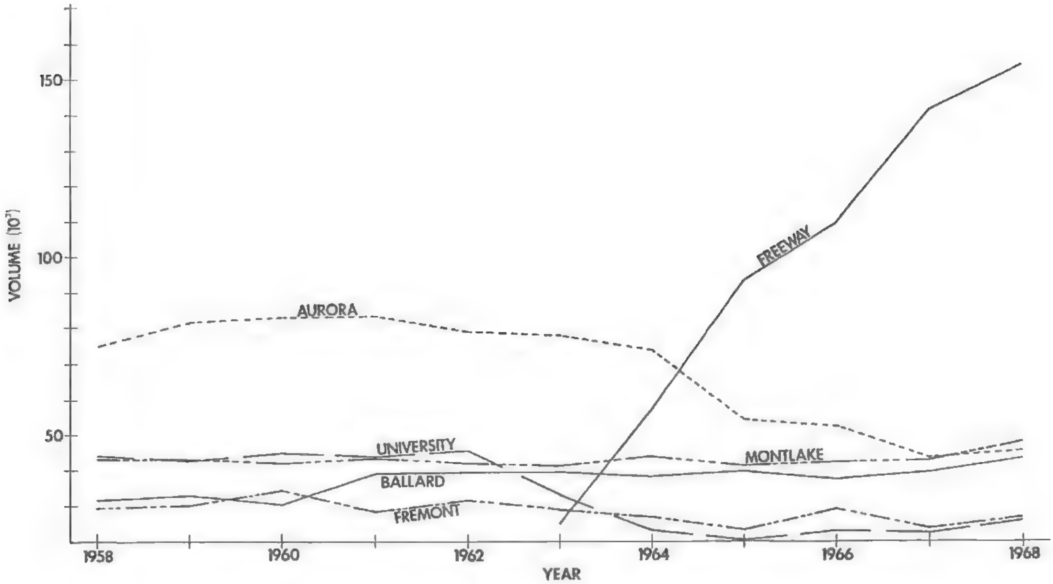

Figure 2. Lake Washington Ship Canal screenline crossings, 1958-68.

because there are several similarities between the traffic on these bridges. This provides a basis for travel time comparisons with data from Route 2. Thus, the 1968 Freeway Bridge volume is made up of the following: crossings diverted from arterials plus growth—80,000; crossings generated, with Route 2 as the alternate—35,000; crossings generated, with Route 3 as the alternate—38,000; and total crossings—153,000.

There are two methods of approaching the time benefit determination. It is possible to evaluate the time savings for each section of the five test routes and multiply this by the section volume. The difficulty in determining the significance of small differences in section travel times suggests that a more realistic approach would be to determine an average test route volume and multiply it by the time savings. This second method was implemented by summing the vehicle-miles of travel on each section of a test route and dividing this figure by the route length. Not unexpectedly, it was found that ratios of annual bridge volumes to 1968 bridge volumes were acceptable factors for developing estimates of route volumes for the years between 1962 and 1967. The average 1968 route volumes developed by this method are, for Route 2—15,900 vehicles per day; Route 3—39,100; Route 4—19,000; Route 5—18,200; and Route 6—117,100. Using these figures, the freeway volumes are interpreted as follows: diverted traffic—61,200; generated traffic, alternate Route 2—26,800; generated traffic, alternate Route 3—29,100.

Additional volume information regarding the percentage of travel during the peak hours was required in order to evaluate the travel time savings for the three time subgroupings used in this analysis. The peak hour travel factors for the routes can be estimated from screenline count data (directional K factors). It must be recognized that the peak periods of traffic flow will occur at different times on the several test routes. There will even be variations in the time of the peak hour at different points along a route. For the sake of uniformity, screenline counts for the hours 7:15-8:15 a.m. and 4:30-5:30 p.m. were defined as the peak hours. The results of the peak hour analysis are given in Table 7. For the detailed analysis, there is no justification for establishing "average K factors" for the arterial and freeway routes. Therefore, the final travel time analysis must utilize each of these individual factors.

Classification counts were taken on Routes 3 and 6, with vehicle groupings established on the basis of the test vehicle types. Foreign cars were included in the compact

TABLE 7

PERCENT OF AVERAGE DAILY TRAFFIC BY TIME OF DAY[a]

(Directional K Factor)

Route	Direction	Morning Peak	Evening Peak	Off-Peak
2	Northbound	6.5	12.6	80.9
	Southbound	10.1	8.2	81.7
3	Northbound	4.5	15.3	80.2
	Southbound	15.6	5.6	78.8
4	Northbound	5.2	7.4	87.4
	Southbound	8.6	7.5	83.9
5	Northbound	7.5	8.3	84.2
	Southbound	7.9	9.3	82.8
6	Nothbound	4.6	12.2	83.2
	Southbound	15.0	6.7	78.3

[a]Data for Routes 2, 3, 5, and 6 are based on 1968 Lake Washington Ship Canal screenline crossings. Data for Route 4 are based on 1968 screenline counts south of Pike St.

TABLE 8

VEHICLE CLASSIFICATION COUNTS, PERCENT

Vehicle Category	Arterial Route 3[a]	Freeway Route 6[b]
Peak Hour, Major Direction		
Compact[c]	17.6	15.8
Sedan	72.1	71.9
Pickup	9.3	10.6
Composite passenger vehicle	99.0	98.3
Medium Truck	0.9	1.0
Heavy Truck	0.1	0.7
Peak Hour, Minor Direction		
Compact[c]	18.9	21.8
Sedan	66.6	63.0
Pickup	9.1	10.4
Composite passenger vehicle	94.6	95.2
Medium Truck	5.3	2.7
Heavy Truck	0.1	2.1
Off-Peak Periods, Both Directions		
Compact[c]	18.4	19.7
Sedan	64.5	65.2
Pickup	10.5	8.8
Composite passenger vehicle	93.4	93.7
Medium truck	5.4	3.0
Heavy truck	1.2	3.3

[a]Route 3, Aurora Ave. N. at Comstock.
[b]Route 6, Seattle Freeway at Roanoke.
[c]Compact classification includes both foreign and compact vehicles.

group, under the assumption that their travel times would not differ significantly from the travel times for the compact vehicle, which in turn are identical with those for the sedan and pickup truck, as summarized in the data for the composite passenger vehicle. The results of the vehicle classification survey are given in Table 8. It can be seen that the composite passenger vehicle constitutes between 93.4 and 99.0 percent of the traffic. In extending these results to the other arterial routes, it is assumed that no heavy trucks (i.e., vehicles 4 and 40) use Routes 2, 4, or 5, and that medium trucks (i.e., vehicles 5 and 50) will not operate on Routes 4 or 5.

The evaluation of time savings on each route is in essence a matrix multiplication process, using the previously presented data as elements. The procedure can be summarized as follows:

$$B_{k,a} = U\,(V_{1i})\,(P_{ij})\,(T_{i1})$$

where

$B_{k,a}$ = time benefit per day on Route k for vehicle a;
U = a scaler, equal to one-half the route volume;
V = a 1×6 matrix whose components are the vehicle classification percentages;
P = a 6×6 diagonalized matrix whose nonzero components are the respective peak hour travel factors;
T = a 6×1 matrix whose elements are the time saved by vehicle on a route; and
i,j = subscripts of time subgroupings (e.g., $i = 1$ for morning peak hour northbound; $i = 2$ for evening peak hour northbound; . . .; $i = 6$ for off-peak southbound).

This procedure could be extended, using larger matrices to provide the total benefit in one calculation. Because this phase of the analysis was not computerized, the extended procedure was not used.

In evaluating the benefit for traffic currently using the freeway, a slightly more complex procedure, recognizing the difference in benefits between the diverted and

generated traffic, must be used. The time saving for diverted traffic is actually equal to the difference in travel time between the improved condition (1968 with freeway) and the condition that would have existed if the freeway had not been built (1968 arterial with no freeway). The latter condition does not exist and therefore is not measurable. It is conservatively approximated by the 1962 arterial travel time. The generated traffic for the year 1968 enjoys a travel time benefit equal to the difference between the freeway and arterial travel times in 1968. Lacking other information, it is assumed that the peak hour factors and the vehicle classification factors are the same for the diverted and generated traffic.

Two additional factors were developed, one for the freeway and one for the arterials, to convert the average daily traffic into annual volumes and to simultaneously convert the result from minutes per day to hours per year. The annual savings in hours for the various types of vehicles are given in Table 9. The effect of diverting traffic from the arterials has already been discussed. There is good cause to ascribe the concommitant arterial savings in travel time to the category of freeway benefits. However, the travel time changes on Routes 4 and 5 are definitely not due to freeway operation, but rather have resulted from arterial improvements, such as signal progression and parking and turning restrictions.

Conversion to Monetary Terms

In interpreting the financial significance of Table 9, consideration must be given to two supplementary pieces of information: vehicle occupancy and the value of time. The value of the former is easily approximated from data gathered in urban transportation studies or other special studies. For the test routes studied, values of 1.5 persons per vehicle on arterials and 1.3 persons per vehicle on the freeway can be used. These values represent averages, but their reasonableness has been verified by spot studies conducted at various points along the routes. They are also in accordance with generalized results published by the Puget Sound Regional Transportation Study (3).

It is not within the scope of this study to develop a value of time. Rather, based on the research by others, the task is to select appropriate time values and apply them to the data given in Table 9. Such a process must, of course, consider the variable time values associated with various trip purposes.

Values of time savings to commercial vehicles have been established by Adkins, Ward, and McFarland (4). Table 35 in their report (4) lists the 1965 values of time savings components (interest, wages, etc.) for 18 cargo vehicle types operating in the Pacific (ICC) Region. Adjusting the values to 1968 at a growth rate of approximately 5 percent per year provided the following information:

Vehicle 40	3S2, diesel, light, van	\$7.20 per hour
Vehicle 50	S. U. 2-axle, gasoline, van	\$4.77 per hour

With respect to passenger vehicles, a study at the Stanford Research Institute (5) found the average time value to be \$2.82 per person per hour. This value is in accord with the research of others (6). There is little hesitancy in applying this value to commuting motorists, who were in fact the sources of information for these studies. The group of noncommuters, who make up the bulk of traffic in the off-peak hours, is not correctly represented by this figure, however. Those persons who are traveling during working hours most certainly have a higher value associated with their companies' time, whereas others such as shoppers may

TABLE 9

TIME BENEFIT

Vehicles	Route	Time Saved, Vehicle Hours per Year	
		Due to Freeway	Due to Other
100/200	2	84,300	–
	3	673,400	–
	4	–	23,000
	5	–	-25,400
	6	7,626,100	–
Total		8,383,800	-2,400
4/40	3	0	–
	6	328,600	–
Total		328,600	–
5/50	2	-6,600	–
	3	-16,600	–
	6	179,400	–
Total		156,200	-2,400

value their time less. Hypothesizing that 40 percent of the daily traffic is composed of commuters (at $2.82 per hour), that 20 percent are traveling during working hours (at $4.00 per hour), and that 40 percent are persons making nonwork trips (at $1.40 per hour, average), then the composite value of time would be $2.50 per person per hour (3).

By the nature of the problem, this value is difficult if not impossible to verify. Certainly, it represents a reasonable value. It is in accord with the toll paid by motorists on a toll bridge in the Seattle area. This value provides a method of transforming the benefit coordinates to a system where they are more recognizable.

The application of these values to the time savings provides an answer in monetary terms. The values obtained for the year 1968 are as follows: passenger vehicles—$27,626,000; commercial vehicles—$3,111,000; and total time benefit—$30,737,000. To provide a frame of reference, this amount is 12 percent of the total construction costs for Route 6. It should be noted that the staggered opening of the freeway prior to 1968 would have severely limited the size of previous benefits. Similarly, the benefit in coming years will be decreased as volumes and travel times increase. Any conclusion that the freeway will "pay for itself" in travel time savings alone in 8 or 9 years must be immediately rejected.

ANALYSIS OF VEHICLE OPERATING COSTS

Despite the overwhelming amount of the apparent savings in travel time, the freeway may also provide a sizable benefit by reducing the vehicle operating costs incurred in making a trip. However, there is little current information comparing the costs between freeways and arterials. This portion of the paper will develop a methodology for comparing vehicle operating costs and, based on the data gathered in the study, will evaluate the net benefit in fuel savings resulting from freeway operation.

Fuel Consumption Analysis

There are two major problems associated with the analysis of fuel consumption: the measurement of data and the separation of changes resulting from improvements in vehicles and fuel from those changes resulting from highway improvements. The former problem was solved by using the fuel meter and the burette board, as discussed previously. Although only minor recognition has been given to the fuel meter, it is recognized that the accuracy of fuel consumption data for passenger vehicles obtained in this study would not have been possible without it.

The second problem is related to the impact that nonmeasured elements may exert on the analysis. If an improvement in the fuel consumption rate is observed, it is important to identify the cause of the improvement. Consideration must be given to the quality of the fuel, for example. Although it is common knowledge that the fuel octane rating has continued to increase in recent years, it is not generally recognized that this has virtually no effect on fuel consumption. The internal energy of fuel, which has remained relatively constant, is more closely related to fuel use. The improvements brought about by fuel additives are real, but appear to be minor in comparison with other variables.

However, vehicular changes can have a significant effect on fuel consumption. The combustion process may be made more efficient, rolling resistance can be reduced, drive train efficiency can be improved, and so forth. It is not feasible to analyze each possible improvement separately. Rather, the net result of fuel and vehicular improvements can be measured by determining the fuel consumption of the test vehicles at constant speeds. For this purpose, Test Route 7, a 12.8-mile section of Interstate Freeway south of Seattle, was used for vehicle calibration. The vehicles were driven at a series of constant speeds in both the northbound and southbound directions. The vehicle speedometers served as a guide to the drivers in maintaining a constant speed. Actual overall speed was computed from the travel time recorded by the observer. The fuel data—counts on the FM 201 for the fuel meter and milliliters for the burette board—were adjusted for the effect of temperature and were summarized in gallons, miles per gallon, and gallons per mile. Because of the difficulty of averaging fuel consumption in miles per gallon, final fuel analysis was based on the average gallons of fuel used.

The data from the series of vehicle calibration runs are given in Table 10. For the low-speed runs with vehicles 10 and 20, there is some doubt that the automatic transmission shifted into high gear. This is unfortunate, because in the analysis process there is a need to interpolate the fuel consumption rate at speeds in the 20- to 30-mph range.

The results of the calibration testing of the passenger-type vehicles indicate that there is a definite improvement in fuel consumption rates at constant speeds for the 1968 test vehicles compared to the 1962 test vehicles. The improvement is greatest in the range from 25 to 40 mph. It tapers off at both higher and lower speeds.

The calibration data for vehicles 2 and 20 are shown in Figure 3. For these vehicles, the maximum improvement of 21 percent is realized at a constant speed of 35 mph. The improvement at 70 mph is only 7 percent. These improvements are due to the previously mentioned vehicular and fuel differences.

The calibration curves can be used to assign the changes in fuel consumption to two separate causes—vehicular and fuel improvements, and highway improvements. The procedure used is to develop a factor relating the two calibration curves at a given speed. To facilitate subsequent calculations, the fuel factor was defined as

$$f(x) = \frac{\text{1968 vehicle calibration curve in MPG at speed x}}{\text{1962 vehicle calibration curve in MPG at speed x}}$$

where f(x) is the fuel factor at speed x and MPG is miles per gallon.

The fuel factor converts the gallons of fuel used by a 1968 test vehicle into the number of gallons that would have been used by the corresponding 1962 test vehicle if the latter were used in the after study. The 1968 test vehicle enjoyed the benefit of decreased travel time and improved smoothness of traffic operation. The magnitude of this benefit is given by the difference between the adjusted 1968 fuel consumption and the fuel consumption measured in 1962. In most cases, the before and after travel speeds are not equal. The calibration curve accounts for this fact by providing the factor that adjusts fuel consumption to the 1968 speed. The 1968 speed is used because that is the speed at which the 1962 vehicles would have operated in the after study.

Obviously, the variations in fuel consumption characteristics among the several test vehicles preclude the use of a composite vehicle. However, for each vehicle it is possible to combine the data from several time periods. Analysis was based on three time subgroupings:

1. Northbound morning peak hour and southbound evening peak hour (direction of minor traffic flows);
2. Northbound evening peak hour and southbound morning peak hour (direction of major traffic flows); and
3. Northbound off-peak and southbound off-peak.

There are several advantages associated with this method of analysis. The peak hour screenline counts showed that the percentage of average daily traffic occurring during the two time components of subgroup 1 are comparable. The same equivalence is shown by the components of subgroups 2

TABLE 10

FUEL CONSUMPTION RATES AT CONSTANT SPEED ON TEST ROUTE 7

Vehicles	1962		1968	
	Average Speed (mph)	Fuel (mpg)	Average Speed (mph)	Fuel (mpg)
1/10	18.335	23.553	19.247	(22.368)[a]
	28.907	21.659	28.777	33.277
	38.607	21.504	38.124	26.006
	48.291	20.189	48.086	23.949
	56.407	16.574	57.907	21.387
	66.210	14.022	68.225	20.554
2/20	19.767	19.573	20.533	21.352
	29.635	19.386	31.424	23.096
	39.053	18.557	41.745	22.359
	49.001	17.467	51.732	19.156
	58.760	16.141	60.844	17.570
	69.240	14.328	70.674	15.589
3/30	30.233	22.879	32.172	26.504
	38.925	20.763	39.608	24.978
	49.164	17.527	50.875	21.531
	59.213	14.826	59.054	18.816
	69.069	11.771	69.664	13.946
4/40	29.265	6.273	29.892	7.081
	38.881	6.578	39.995	7.410
	47.735	6.315	48.504	7.231
5/50	31.825	9.341	28.486	9.791
	41.968	10.055	37.878	8.430
	52.136	7.693	47.338	7.048
			57.387	5.640

[a] It is quite possible that vehicle 10 was not operating in high gear at 20 mph.

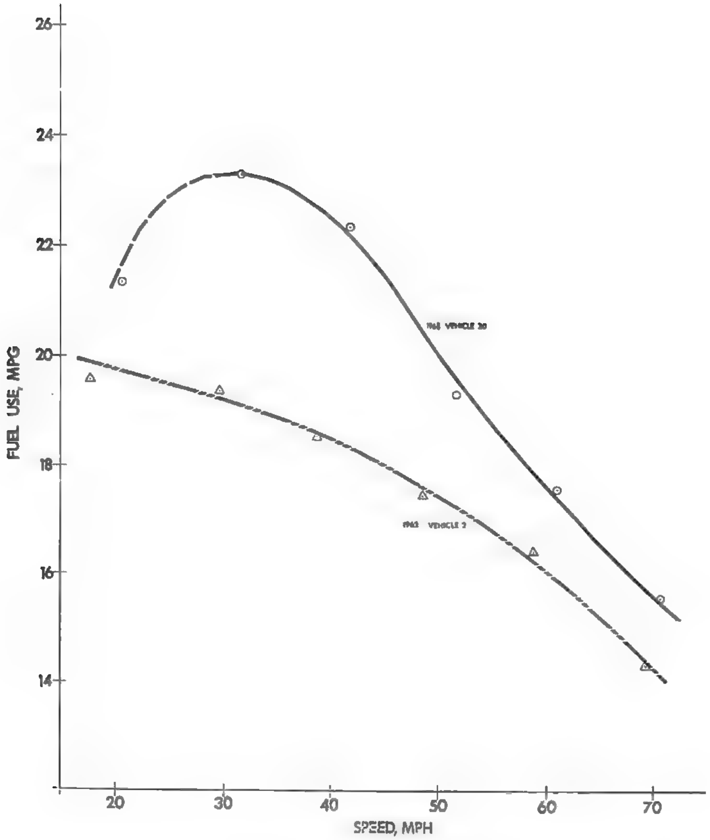

Figure 3. Fuel use comparison of standard vehicle, 1962 and 1968.

and 3 respectively. In addition, the topography of Seattle is such that the southbound trips consistently enjoy better fuel mileage than the northbound trips. This method permits analysis on a round-trip basis, thus minimizing the influence of topography. It should be noted that this subdivision of the data represents a combination of the travel time subgroupings.

The analysis is similar to the travel time computations in the sense that there are two types of benefits: those accruing to persons who continue to use the arterials, and those accruing to freeway users whose alternate route would have been Route 2 or 3. The improved operating conditions provided by the freeway are in part counterbalanced by the poorer fuel economy obtained at higher freeway operating speeds.

The development of fuel comparisons for vehicles 2 and 20, which represent by far the largest segment of the vehicle population, is given in Table 11. Analysis is not shown for Route 4 because the low travel speeds on this route lie outside the range of applicability of the calibration curves. In addition, the minor traffic volume relief experienced on this route suggests that any improvement in operation is not due to the freeway.

For the standard sedan, there are significant fuel savings for the peak hour traffic in the major direction of flow on Routes 2 and 5. The actual savings in gallons are quite small, however. A comparison of fuel consumption between the freeway and the alternate arterial routes indicates a definite user benefit for persons driving standard sedans. A commuting motorist could save up to $1\frac{1}{2}$ gallons of fuel per week by using the freeway.

TABLE 11

FUEL CONSUMPTION COMPARISONS FOR VEHICLES 2 AND 20

Route	Time Subgroup[a]	1968				1962 Fuel[c]	Fuel Savings[c]	Percent Savings
		f(x)	Speed[b]	Fuel[c]	Fuel, adj.[c]			
2	1	1.12	22.7	0.2736	0.306	0.321	+0.015	4
	2	1.07	21.1	0.2868	0.306	0.363	+0.057	16
	3	1.13	23.5	0.1819	0.320	0.320	0	0
3	1	1.20	32.2	0.8388	1.011	0.957	-0.054	-6
	2	1.20	30.8	0.8557	1.029	1.052	+0.023	2
	3	1.21	34.4	0.8379	1.012	0.993	-0.019	-2
5	1	1.11	22.4	0.3699	0.411	0.396	-0.015	-4
	2	1.14	23.8	0.3385	0.386	0.439	+0.053	12
	3	1.16	25.0	0.3339	0.387	0.395	+0.008	2
6	1	1.10	60.2	0.2380	0.262	0.321	+0.059	18
(Alt. 2)[d]	2	1.17	48.9	0.2257	0.263	0.363	+0.100	27
	3	1.12	57.2	0.2361	0.264	0.320	+0.056	17
6	1	1.11	58.7	0.7903	0.876	0.957	+0.081	8
(Alt. 3)[e]	2	1.16	50.2	0.7692	0.891	1.052	+0.160	15
	3	1.12	57.0	0.8054	0.899	0.993	+0.094	9

[a]1 indicates average of northbound morning and southbound evening; 2 indicates average of northbound evening and southbound morning; 3 indicates average of northbound off-peak and southbound off-peak.
[b]In miles per hour.
[c]Fuel measured in gallons.
[d]Section of freeway from Stewart St. to N. 85th St.
[e]Entire length of Route 3.

The success achieved in the area of fuel consumption analysis for vehicles 2 and 20 was unfortunately not duplicated in the comparative analyses of the compact sedan and the pickup truck. There are several reasons for the shortcomings. Primarily, there is a minimal amount of data for these types of vehicles in the peak periods in the 1962 study. Vehicles 2 and 20 made more peak hour runs (excluding Route 4) than did vehicles 1, 3, 10, and 30 combined. This problem was circumvented in the travel time analysis by the uniformity of the data and the development of the composite vehicles. Also, vehicles 1 and 10 should have had identical calibration curves because they were virtually identical vehicles. However, vehicle 10 achieved up to 46 percent better fuel mileage on the calibration section. On Test Routes 2, 3, and 5, the unadjusted fuel consumption was not statistically different from that of vehicle 1. Because of the conflicting fuel data, it is not possible to make statistically significant statements about the possible nature of fuel consumption benefits for compact vehicles.

Vehicle 30, the 1965 pickup truck, demonstrated similar inconsistencies, although they were not as pronounced as for vehicle 10. The only increase in fuel consumption on arterials that is significant is on Route 2, period 3. A comparison of fuel consumption for Route 6 versus the two alternate routes indicated an average increase in fuel consumption during period 3. The results for vehicle 30 suggest that, for a pickup truck with a 6-cylinder engine, the increased fuel consumption at freeway speeds is not wholly balanced by the improvement in smoothness of operation.

The analysis of truck fuel consumption was simplified by the fact that professional truck drivers drive in a consistent manner. As a result, meaningful analysis can be performed on the comparatively small number of off-peak runs. Because of the small variance of the data, some changes in fuel consumption of 10 percent were significant at the 95 percent confidence level. On this basis, there was no benefit for vehicle 40 on Route 3, but there was a positive benefit for the freeway compared to Route 3. On the other hand, vehicle 50 used significantly more fuel in off-peak comparisons of the arterials and the freeway. The reasons for the unusual results for vehicle 50 are not intuitive.

The most reasonable explanation is that the calibration curves do not represent the relative fuel consumption under normal traffic conditions. As a result vehicle 50, which has 30 percent more horsepower and 10 percent more engine displacement than vehicle 5, does not display similar fuel consumption characteristics. On the other hand,

vehicle 50 is more typical of the van trucks on the road in 1968 than is vehicle 5. The trend is toward more powerful trucks with larger engines. Apparently, the trucking industry feels that the poorer fuel consumption achieved by these vehicles is more than accounted for by the increased range of service they provide.

The statistically significant changes in fuel consumption are summarized in Table 12. Because of the problems associated with the fuel data from vehicle 10, it was not possible to evaluate the significance of the changes in fuel consumption for this vehicle. The standard sedan shows a notable improvement on the freeway, with minor improvements on the arterial routes. Vehicle 40, the diesel truck, has an unexpectedly high fuel savings on the freeway, although it consumes fuel at the rate of 6 to 7 miles per gallon.

The total amount of fuel saved is calculated by a method similar to the matrix procedure used for travel time analysis. The decreases in fuel consumption were included as negative benefits. Peak hour percentages were regrouped to correspond to the revised time subgroupings. With this basis, the following fuel savings in gallons per year were established:

Category	Gasoline	Diesel
Arterials	-318,000	—
Freeway	1,560,000	458,000
Net benefit	1,250,000	458,000

It is difficult to define the average cost of fuel. A gasoline price war in an urban area may cause prices to change drastically. A drop in price from 33 cents per gallon to 30 cents per gallon, an apparent 10 percent reduction, is actually an 18 percent reduction if the fuel tax (9 cents per gallon state tax and 4 cents per gallon federal tax) is subtracted from the price. Of course, for analysis purposes it is mandatory that the tax be subtracted from the cost. The fuel tax is not an inherent part of fuel costs. Rather, it represents the simplest and perhaps the most equitable method of highway user taxation.

Returning to the question of fuel price, a spot study of advertised fuel prices at major brand stations in the Seattle area on a day during the study discovered a range of 33.9 to 37.9 cents per gallon for regular gasoline. Within the past year, these prices have dropped as low as 29.9 cents per gallon. The prices for premium grade gasoline are normally 3 to 4 cents per gallon more than the regular grade.

A study of consumer awareness of motor fuel prices by Cook (8) found that at the moment of purchase only 50 percent of Virginia drivers knew within 1 cent the price they were paying for gasoline. Motorists buying economy or regular grades of gas were no more price-conscious than those purchasing premium gas. Among those who were aware of the price, only 26 percent cited cost as a factor in their choice of fuel. Manufacturer's recommendations or engine requirements were often given as the reason for selecting a grade of fuel. Based partially on these results, an average Seattle area fuel cost of 35 cents per gallon was selected. This value accounts for the costs of the various grades and also for price fluctuation. This cost must be reduced by the 13 cents of federal and state fuel taxes. Thus, the value for analysis purposes is 22 cents per gallon. It should be remembered that this cost is a variable from

TABLE 12

SUMMARY OF SIGNIFICANT FUEL CONSUMPTION BENEFITS[a]

Route	Vehicle	Time Subgroup	Fuel Savings per Vehicle (gallons)
2	20	2	0.057
	30	3	-0.056
	50	3	-0.313
3	50	3	-0.414
5	20	2	0.053
6(Alt. 2)	20	1	0.059
		2	0.100
		3	0.056
	30	3	-0.060
	50	3	-0.173
6(Alt. 3)	20	1	0.081
		2	0.160
		3	0.094
	30	3	-0.234
	40	3	0.435
	50	2	-0.254

[a]No changes attributable to the freeway were found on Route 4. The improvement for vehicle 20, Route 5, time period 3, was due to arterial improvements.

place to place. The price of diesel fuel is slightly less, depending on the grade and, in some cases, the quantity bought. For diesel fuel analysis, a cost of 20 cents per gallon is used. This value is intended to represent an average of the generally lower cost of diesel fuel and the quantity discount given to trucking firms.

Applying these costs to the number of gallons saved produces a total benefit in 1968 of $366,000. Of this benefit, $91,000, or 25 percent, is realized by the diesel trucks. The apparent negative fuel benefits for the pickup and van trucks cut sharply into the net benefit.

In comparison with the travel time benefit of $30 million annually, the savings on fuel is almost negligible. Although it does exist, it is probably not noticed by the general public. The weekly fuel savings for the sedan is approximately 1 gallon if 5 round trips per week are made on the freeway. The actual net benefit is, of course, the result of a summation of incremental savings accruing to individual users.

In a sense it is unusual that a fuel savings was realized. Despite the high rate of fuel consumption at freeway speeds, as indicated by the calibration curves, the freeway benefit actually results from a comparison of fuel use at constant speeds versus the fuel use under stop-and-go conditions on arterials. Because of the sensitivity of fuel consumption to operating conditions and to topography, it may be difficult to duplicate these results at another point.

In analyzing the fuel data, several unsuccessful attempts were made to establish a relationship between fuel consumption and other variables on which information was available. These approaches are worthy of note because their negative results may provide a guideline for subsequent research.

It was suggested that a relationship might exist between test route overall speed and fuel consumption. For the arterial test routes, no significant correlation could be established between these two variables. However, plots of the freeway data, as might be expected, follow the trend of calibration curves. On section 6 of the freeway (Stewart St. to the Freeway Bridge), fuel consumption was actually less than on the calibration section at the same speed. This does not impair the integrity of the calibration curves, however, because they do not define an absolute fuel consumption, but rather provide a basis for comparison of vehicles under identical conditions.

An analysis of fuel consumption for specific runs, as related to actual 15-minute traffic volumes at the times the runs were made for a section of the freeway, proved to be inconclusive. A general trend of decreasing fuel consumption with higher volumes was discernible, but the data were not consistent enough to permit meaningful conclusions to be drawn.

The logical conclusion from the fuel analysis portion of the study is that positive benefits in the area of vehicle operation costs can result from freeway operation. Special attention has been devoted to fuel consumption, although it is conceivable that there may be concurrent savings in oil and tire costs and possibly vehicle maintenance costs. Additional variables, specifically the quality of oil and tires used, suggest that a meaningful study of the benefits associated with these items would be quite difficult.

SUMMARY

Of the two components of highway user benefits that have been analyzed, the time savings benefit is by far the largest in magnitude and the most obvious to the road user. The fuel savings benefit, although small, is perhaps realized by groups of persons within our polarized society that have simultaneously embraced the concepts of the economical (foreign) car and the luxury of the high-powered vehicles. There is a great deal of evidence to suggest that the public is not concerned about saving a few cents worth of fuel. On the other hand, there is an apparent obsession among many users to minimize the amount of travel time required for making a trip. The impact of these factors on the analysis is virtually nonexistent, however, as they merely add insight in interpreting the results.

If the highway engineer is concerned with the optimization of user benefits resulting from urban freeway construction and operation and the justification of capital expenditures on the basis of these benefits, this study would indicate that, in the case of urban

freeways, the analysis of benefits might well be concentrated in the area of travel time savings. A supplementary report indicates that the accident reduction benefit for an urban freeway may be significant, although on a per-vehicle-mile basis it is less than 10 percent of the time savings benefit.

Although the annual time savings benefit exceeds $30 million, an amount exceeding the annual freeway cost, there is some doubt that the net non-user benefits that have resulted from freeway operation are characterized by a negative value and thus may distract from the total benefit. Although it was not within the scope of this investigation to evaluate indirect benefits, their monetary importance could easily exceed that of fuel savings. Therefore, before detailed evaluation of this form of user benefit is undertaken, consideration should also be given to other benefits of comparable size.

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A General-Purpose Model for Motor Vehicle Operating Costs

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The costs of motor vehicle operation vary over time and from place to place. To deal with the temporal and geographical changes in the unit prices of the various factors that comprise motor vehicle operating costs, this paper discusses a method of estimating motor vehicle operating costs on the basis of physical parameters and quantities that can be related to vehicle characteristics, highway alignment, and traffic conditions. The method relies on a computer program that generates tables of operating costs that are applicable over a wide range of speed and gradient for a specified level of service, highway standard, and surface type. Calculations are carried through in terms of units of consumption, such as gallons of fuel, so that actual costs might be varied to reflect local conditions and changing prices. Each component of operating cost is output for the appropriate range of speed and grade. The program is designed primarily to be used as a substitute for continuously updating such operating cost sources as the AASHO Red Book. A sample output is presented illustrating the use of the model to generate data for a particular combination of vehicle type and level of service, along with summary data for a range of level of service. A series of nomographs that permit hand calculation of operating costs are also presented. The sample problem is then treated by comparing the results of using the computer-generated operating cost tables with hand calculation.

•ROAD USER COSTS are the most important element in total highway costs for almost any reasonable level of traffic volume and are therefore frequently critical in decision-making in highway planning. [No attempt is made here to discuss the use of user costs in highway economy studies of the benefit-cost variety, as numerous references on the subject already exist (1).] One of the major problems encountered in estimating motor vehicle operating costs for use in highway economy studies is to obtain data that are relevant to both the time period under consideration and the particular geographical location of the study. Most currently available operating cost sources suffer from one or more of the following shortcomings:

1. It is difficult to adjust prices to reflect changes over time, because increases in the various components that comprise total operating costs are not uniform. In other words, with fuel, oil, and tire costs combined in an aggregate cost, it is difficult to account for increases in the cost of fuel alone.
2. Similarly, extra-market values such as the value of travel time are often aggregated with market values such as fuel costs in a manner that makes it difficult to adjust total operating costs should some of the extra-market components change.
3. The factor prices that comprise total operating costs may vary significantly from one locale to another.

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4. Often, only automobile costs are treated in any detail, and costs of truck operation must be inferred from the automobile costs for similar operating conditions.

To deal with these problems, a method of estimating motor vehicle operating costs on the basis of physical parameters and quantities has been developed. [A more detailed discussion appears elsewhere (2).]

APPROACHES TO DETERMINING OPERATING COSTS

A variety of techniques can be used to estimate the physical units that determine motor vehicle operating costs. These techniques vary with respect to the level of detail desired and the nature of the data available to describe highway geometry, surface type, driver behavior, and the vehicle itself. In general, all methods attempt to relate consumption rates for such items as fuel and tires to various alignment, vehicle, and operating characteristics. However, considerable choice exists in the selection of the level of detail used to describe the alignment (for example, whether information is provided for 100-ft sections or 1-mile sections), as well as the degree of interaction among vehicles (for example, the choice of using detailed simulation techniques to describe the speed characteristics of a fleet of vehicles or using typical speed profiles).

Basically, four approaches can be used to determine the physical units necessary for estimating motor vehicle operating costs. The first involves hand calculation and the use of basic charts and tables that are available in the literature (3). Where user costs are required only infrequently or where the alignment under study is of uniform character, hand computation may prove satisfactory. The nomographs shown in Figures 1, 2, 3, and 4 have been prepared to facilitate such calculations for the automobile case. A sample calculation is shown on each chart. Similar charts are available for single-unit and combination trucks.

Where alignment is variable and a large number of volume and service conditions must be considered, lengthy hand calculations can be reduced by use of the computer. A simple computer program designed for this purpose is introduced later in the paper. This program generates tables of operating costs per unit of distance over a wide range of speed and gradient. In this case, total operating costs and final results for a particular project would still require some hand calculation.

A third approach makes use of detailed computer simulation programs that can accommodate a wide range of vehicle types, operating conditions, and alignments. An early approach, known as the Vehicle Simulation Program, was developed at the Massachusetts Institute of Technology (4). This method is analogous to the train performance calculators widely used in the railroad industry in that basic laws of physics are used to simulate the movement of a vehicle over a specified alignment in small increments of time, distance, or speed.

The MIT problem-oriented language ICES (Integrated Civil Engineering Systems) contains a subsystem ROAD that includes an updated Vehicle Simulation Program. A modified version of this approach is also reported by Clark (2).

Finally, attempts have been made to determine operating costs by reducing data arrays to a series of equations. These cost equations are useful for evaluating operating costs over a network of highways. They sacrifice accuracy in the interests of computational ease (5).

A GENERAL PURPOSE MODEL

In general, use of an up-to-date operating cost table is adequate for the level of detail used in most highway cost calculations. This is evident from the fact that early attempts to develop detailed vehicle simulation programs referred to in the preceding have never been widely used in highway practice. For this reason, although the background research for this paper dealt with each of the first three approaches, the remainder of this paper concerns the second approach, that is, a computer program that generates tables of operating costs applicable over a wide range of speed and gradient for the specified level of service (6), highway standard, and surface type.

This program is based largely on empirical information already available in tabular and graphical form and, as such, does not involve any simulation technique. For variable

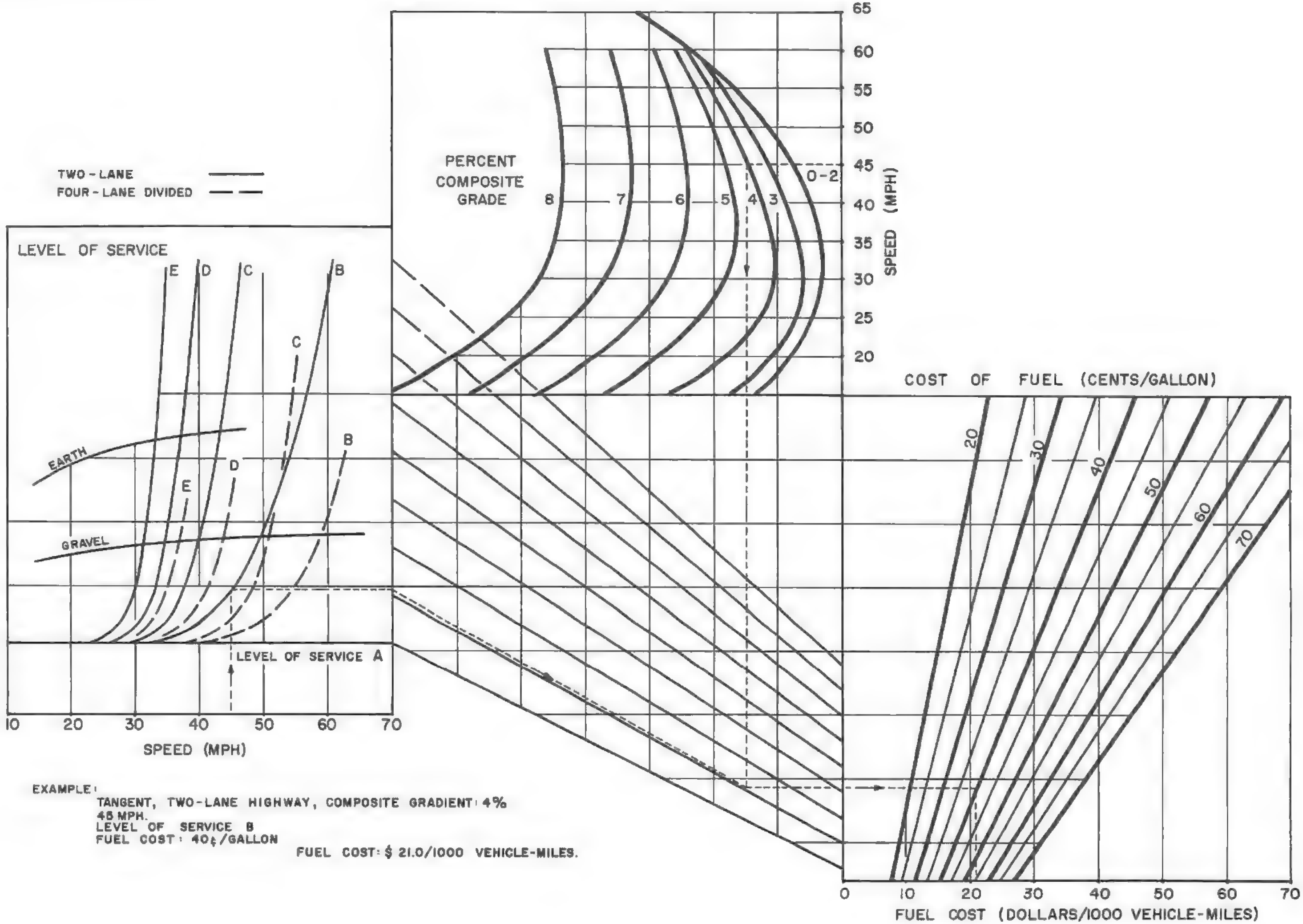

Figure 1. Passenger vehicle fuel costs, tangent rural highways.

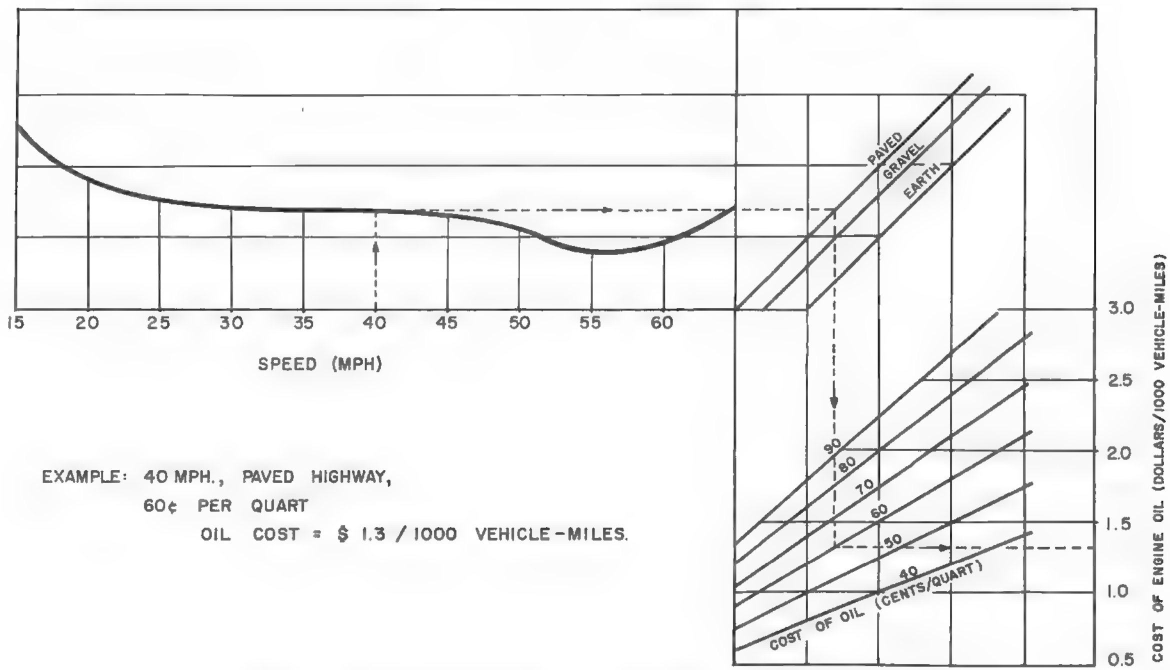

Figure 2. Passenger vehicle engine oil consumption, tangent rural highways.

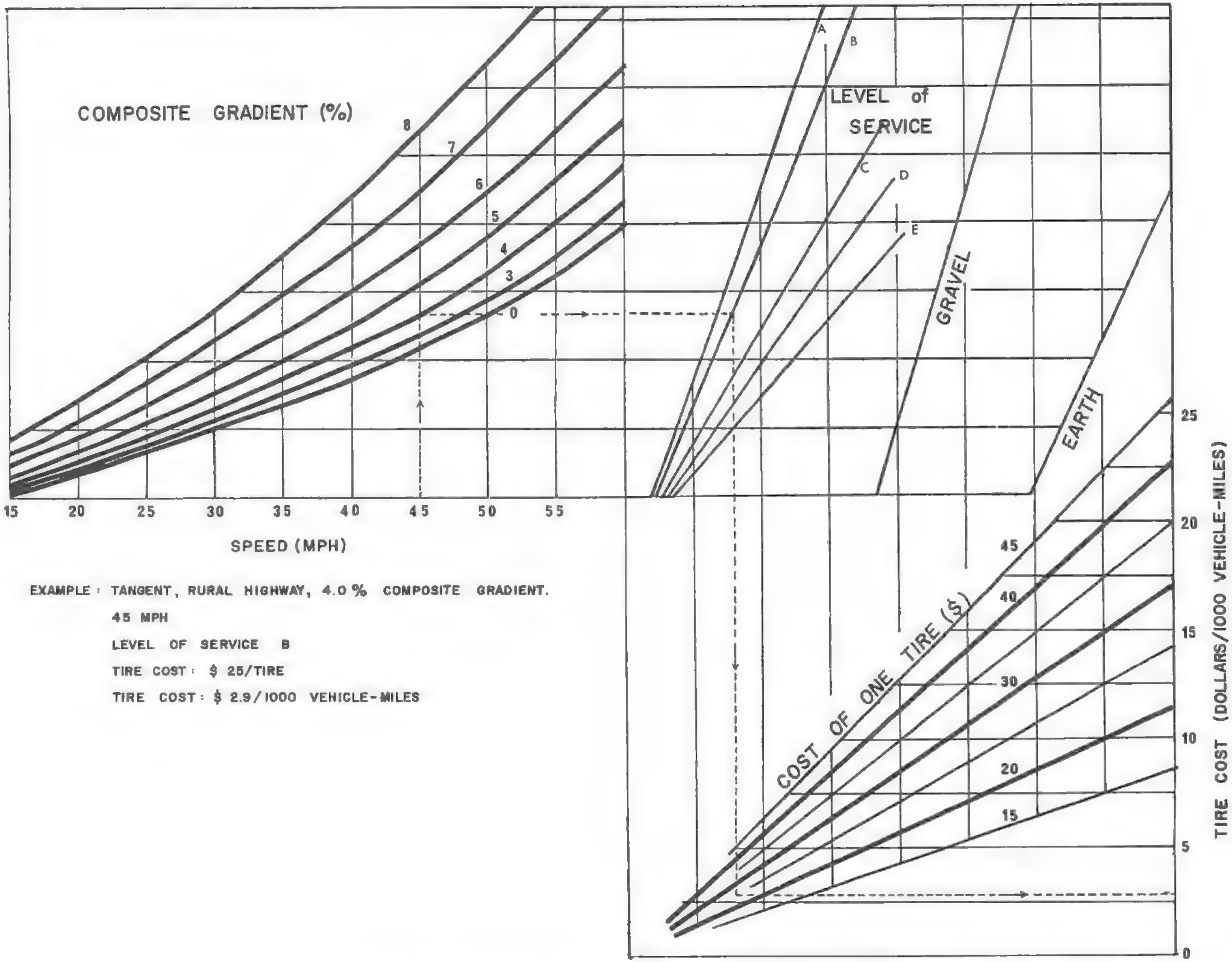

Figure 3. Passenger vehicle tire costs, tangent rural highways.

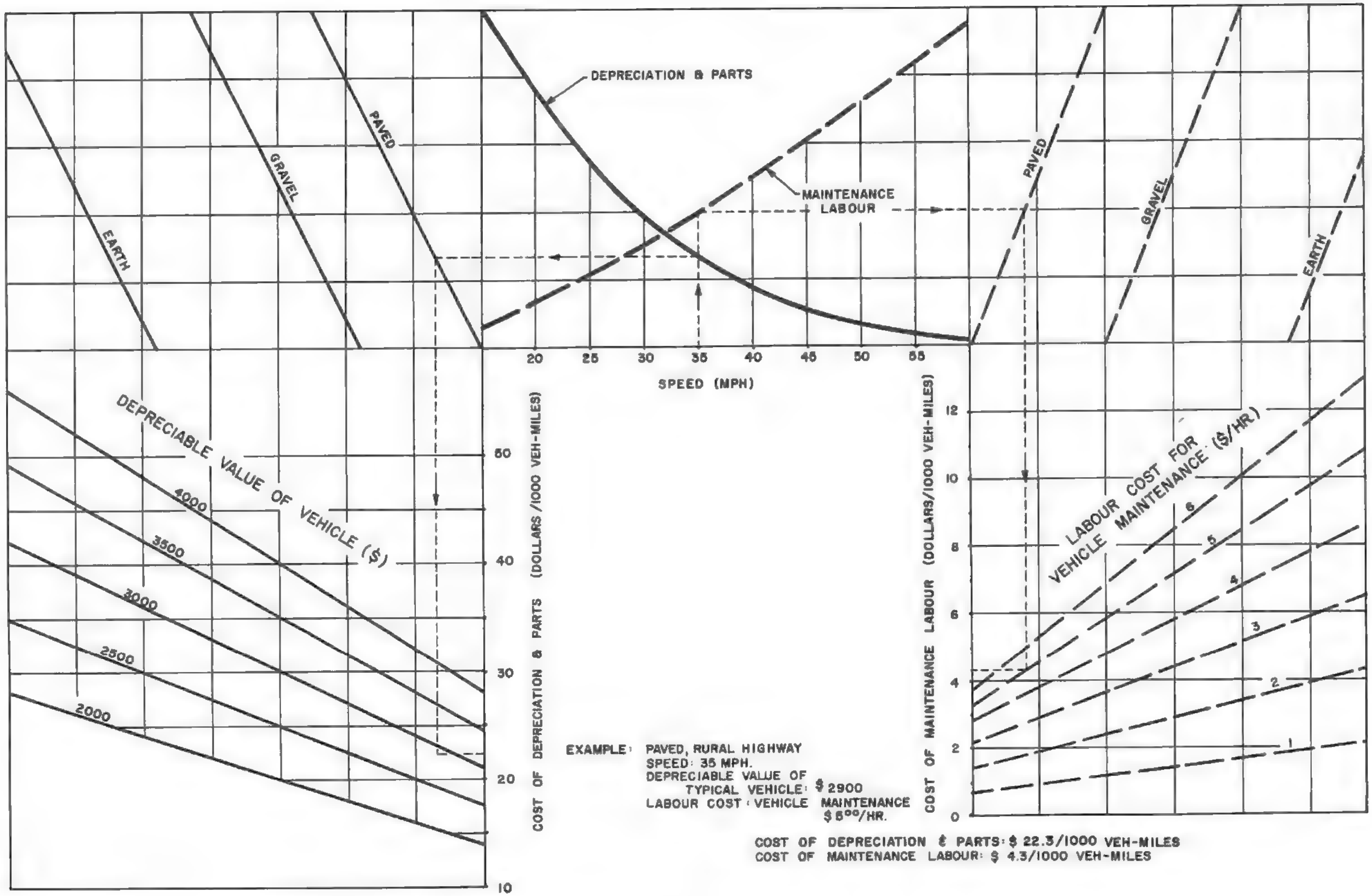

Figure 4. Passenger vehicle maintenance and depreciation costs, tangent rural highways.

volume and alignment conditions, calculation of operating costs for a given project is reduced to application of these table values to the alignment and traffic conditions at hand. The essence of this program is that calculations are carried through in terms of units of consumption (such as gallons of fuel), so that unit costs might be varied to reflect local conditions and changing prices. Although the actual tables generated by the computer program are presented in terms of cost, output can be regenerated easily by varying any or all of the input parameters. The program prepares tables of user costs when supplied with the following general data: vehicle type, surface type, roadway type, level of service, unit costs, range of speeds, and range of grades.

A flow chart for the computer program is shown in Figure 5. Table 1 is an example of the output obtained for a passenger vehicle operating on tangent two-lane highway with level of service B. The input parameters are indicated on the table. Similar tables may be generated for the remaining levels of service or, alternatively, the program may be used to produce a summary table showing the direct operating and time costs for a variety of levels of service, as given in Table 2. Similar tables for truck operation can also be generated. Although the units used in these sample tables are British units, the program accommodates British, U.S., or metric units. In preparing a manual

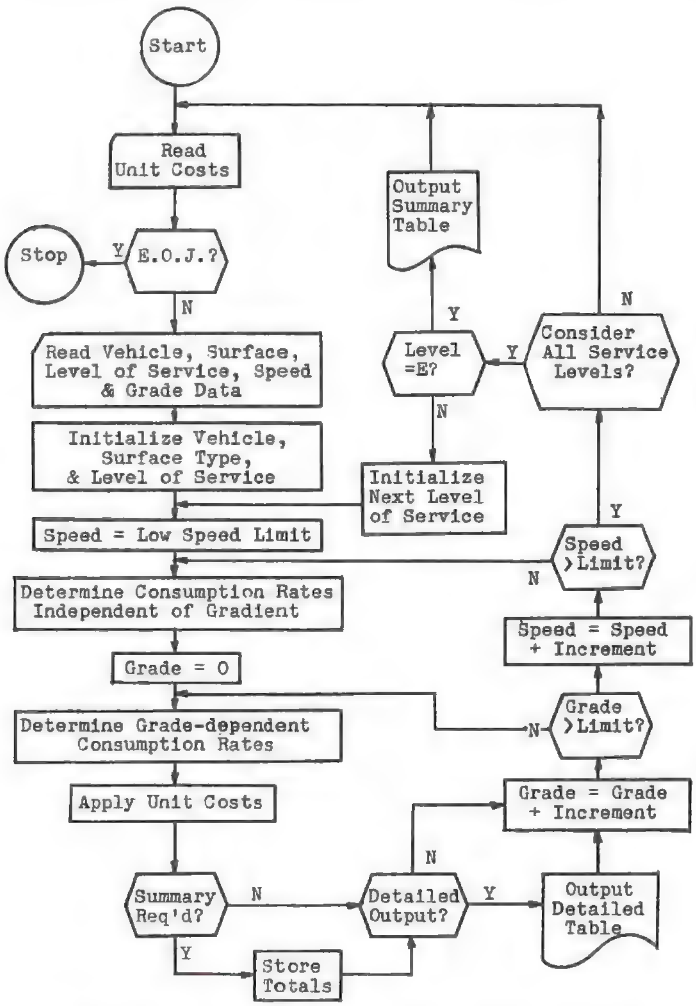

Figure 5. Generalized flow chart for table generation program.

TABLE 1

ROAD USER COSTS FOR PASSENGER VEHICLES IN RURAL AREAS

(Tangent 2-Lane Highways, Paved Surface, Level of Service B)

Speed (mph)	Grade (percent)	Operating Costs, Dollars per 1,000 Vehicle-Miles							
		Fuel[a]	Tires[b]	Oil[c]	Maintenance[d]	Depreciation[e]	Subtotal	Time Cost[f]	Total Cost
36	0	13.5	1.8	1.6	7.3	17.8	42.10	43.1	85.15
	2	13.7	1.8	1.6	7.3	17.8	42.23	43.1	85.29
	4	14.7	2.1	1.6	7.3	17.8	43.56	43.1	86.62
	6	16.8	2.7	1.6	7.3	17.8	46.28	43.1	89.34
40	0	14.0	2.1	1.6	7.4	17.1	42.30	38.7	81.05
	2	14.3	2.1	1.6	7.4	17.1	42.59	38.7	81.34
	4	15.3	2.4	1.6	7.4	17.1	43.83	38.7	82.58
	6	17.1	3.1	1.6	7.4	17.1	46.43	38.7	85.18
44	0	15.2	2.4	1.6	7.8	16.4	43.38	35.2	78.60
	2	15.6	2.4	1.6	7.8	16.4	43.77	35.2	79.00
	4	16.4	2.7	1.6	7.8	16.4	44.93	35.2	80.16
	6	18.1	3.5	1.6	7.8	16.4	47.46	35.2	82.69
48	0	17.2	2.7	1.6	8.2	15.9	45.51	32.3	77.80
	2	17.6	2.7	1.6	8.2	15.9	45.92	32.3	78.22
	4	18.3	3.1	1.6	8.2	15.9	47.05	32.3	79.34
	6	19.8	4.0	1.6	8.2	15.9	49.52	32.3	81.81
52	0	20.4	3.0	1.5	8.6	15.4	48.94	29.8	78.75
	2	20.7	3.0	1.5	8.6	15.4	49.27	29.8	79.08
	4	21.4	3.5	1.5	8.6	15.4	50.38	29.8	80.18
	6	22.9	4.5	1.5	8.6	15.4	52.89	29.8	82.70
56	0	25.1	3.4	1.4	9.0	15.0	53.91	27.7	81.59
	2	25.2	3.4	1.4	9.0	15.0	54.01	27.7	81.69
	4	25.7	3.9	1.4	9.0	15.0	55.07	27.7	82.75
	6	27.2	5.1	1.4	9.0	15.0	57.74	27.7	85.42

[a]Fuel cost = $0.32 per gallon.
[b]Tire cost = $25.00 per tire (plus retreads).
[c]Oil cost = $0.75 per quart.
[d]Labor cost = $3.25 per hour.
[e]Depreciable value = $2,900.00.
[f]Time cost = $1.55 per hour.

TABLE 2

ROAD USER COSTS FOR PASSENGER VEHICLES IN RURAL AREAS AT VARIOUS LEVELS OF SERVICE

(Tangent 2-Lane Highways, Paved Surface)

Speed (mph)	Grade (percent)	Time Costs	Operating Costs, Dollars per 1,000 Vehicle-Miles, for Level of Service							
			A		B		C		D	
			Operate	Total	Operate	Total	Operate	Total	Operate	Total
36	0	43.1	41.7	84.8	42.1	85.2	43.8	86.8	48.1	91.1
	2	43.1	41.9	84.9	42.2	85.3	43.9	87.0	48.2	91.3
	4	43.1	43.2	86.2	43.6	86.6	45.4	88.5	50.1	93.2
	6	43.1	45.8	88.8	46.3	89.3	48.5	91.6	54.0	97.0
40	0	38.7	41.6	80.3	42.3	81.0	45.7	84.5		
	2	38.7	41.9	80.6	42.6	81.3	46.1	84.8		
	4	38.7	43.0	81.8	43.8	82.6	47.6	86.3		
	6	38.7	45.5	84.2	46.4	85.2	50.8	89.6		
44	0	35.2	41.8	77.1	43.4	78.6	51.6	86.8		
	2	35.2	42.2	77.4	43.8	79.0	52.1	87.4		
	4	35.2	43.2	78.5	44.9	80.2	53.8	89.0		
	6	35.2	45.5	80.7	47.5	82.7	57.5	92.7		
48	0	32.3	42.4	74.7	45.5	77.8	58.3	90.6		
	2	32.3	42.7	75.0	45.9	78.2	59.0	91.3		
	4	32.3	43.7	76.0	47.0	79.3	60.7	93.0		
	6	32.3	45.8	78.0	49.5	81.8	64.6	96.9		
52	0	29.8	43.1	72.9	48.9	78.7				
	2	29.8	43.3	73.2	49.3	79.1				
	4	29.8	44.2	74.0	50.4	80.2				
	6	29.8	46.2	76.0	52.9	82.7				
56	0	27.7	44.1	71.8	53.9	81.6				
	2	27.7	44.2	71.8	54.0	81.7				
	4	27.7	44.9	72.6	55.1	82.8				
	6	27.7	46.9	74.6	57.7	85.4				
60	0	25.8	45.6	71.4						
	2	25.8	45.4	71.2						
	4	25.8	46.1	71.9						
	6	25.8	48.0	73.8						

Note: Fuel cost = $0.32 per gallon
Oil cost = $0.75 per quart
Depreciable value = $2,900.00
Labor cost = $3.25 per hour
Tire cost = $25.00 per tire
Time cost = $1.55 per hour

for use in a highway department, the program could be used to generate 40 to 50 tables similar to Table 1 for a number of surface types and vehicle types on two-lane and divided highways, and over the appropriate range of levels of service.

EXAMPLE OF COMPUTER PROGRAM

The use of the computer program can be demonstrated through a simple problem relating to the alignment shown in Figure 6. An alignment U-V-W is under study as a

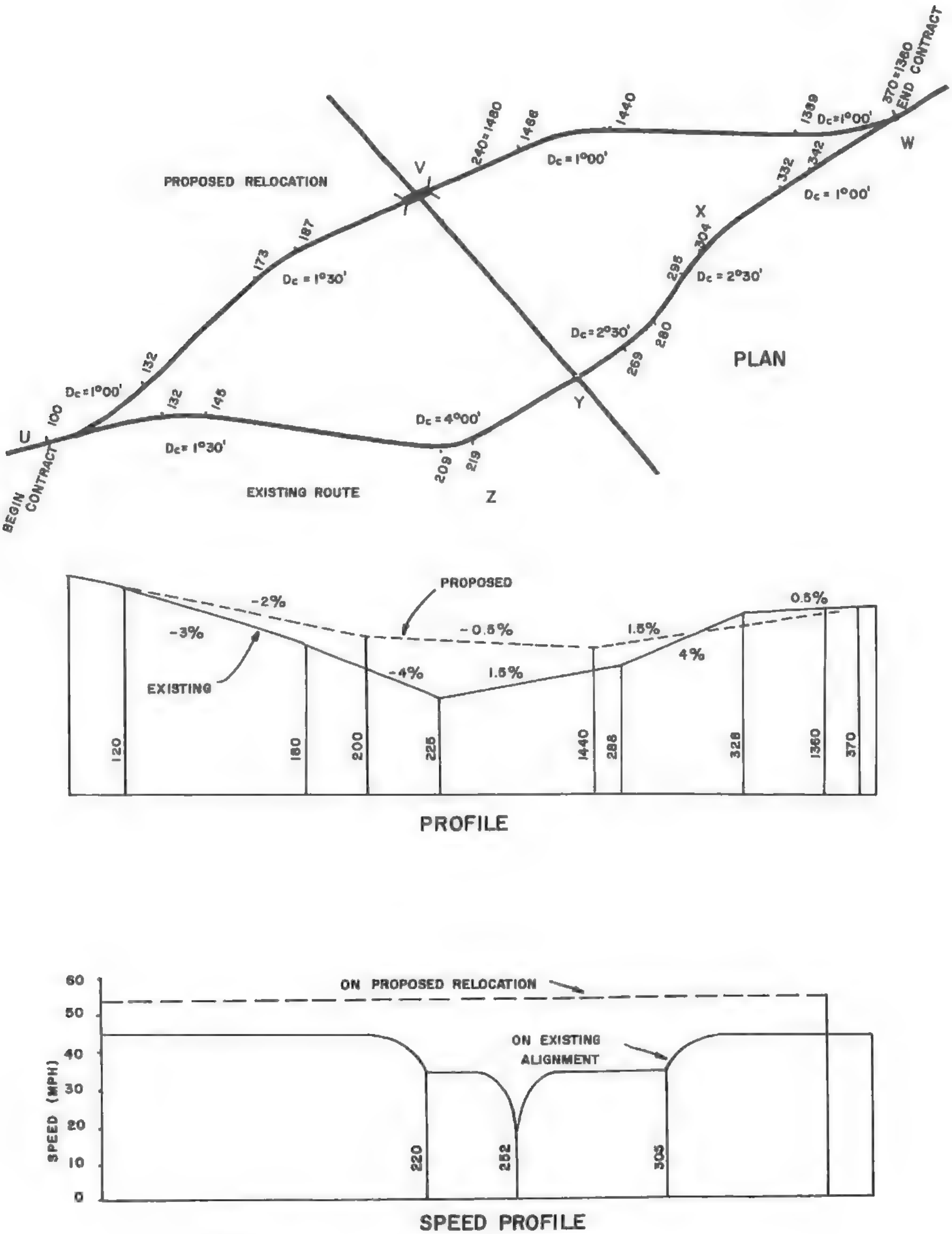

Figure 6. Sketch for example problem.

possible replacement to an existing route U-Y-W. Project life is taken as 20 years and a rate of interest of 5 percent is to be used for analysis. Both routes are two-lane highways with high standard surfacing in a rural area except for development in section X-Z. Five hundred vehicles per hour is taken as representative of the equivalent annual volume over the 20-year life of the project. [The term equivalent annual volume is commonly used to denote a weighted average volume where weighting factors are determined by the interest rate. Effectively, it is the present discounted value of all future volumes multiplied by the capital recovery factor.] The hourly volume is composed of 425 automobiles, 50 single-unit trucks, and 25 combination units. Level of service B is taken as representative of operation on proposed route U-V-W and average running speed is estimated at 53 mph. Sections U-Z and X-W on the existing facility are assumed to operate at level of service B and average running speed of 45 mph. Section X-Z provides level of service C at an average running speed of 35 mph (where flow is uninterrupted). The effect of conflict occurring in this section is to be estimated by one 10-mph speed change cycle per vehicle. That is, speed is assumed to be forced to 25 mph with immediate acceleration back to 35 mph. Stop control at intersection Y delays main-road vehicles for an average of 6 seconds.

Without attempting at this point to carry out the entire analysis, the use of the computer-generated tables can be illustrated for the case of alignment U-Y-W. Because three vehicle types and two levels of service are accounted for, a total of six operating cost tables must be consulted. Each of these tables is similar in form to Table 1. Alternatively, summary tables similar to Table 2 could be consulted.

As shown, each component of total operating costs is output for the appropriate range of speed and grade. Applying these results to the problem simply involves multiplication of computer-calculated costs by the lengths of segments of the project having uniform characteristics. The results obtained by using this procedure are given in Table 3. As indicated, all costs are shown per 1,000 vehicles using the route.

For purposes of comparison, the results of hand computation for the case of automobiles only are given in Table 4. The data necessary for these hand calculations can be obtained from a number of sources as previously mentioned or can be approximated from the series of nomographs shown in Figures 1 through 4 and similar nomographs for single-unit and combination trucks. The computer approach clearly allows for more detailed investigation of the problem by reducing both the time and tedium of calculations. If in the sample problem, for example, unit prices were expected to change over the period of analysis, Tables 1 and 2 could be regenerated by simply altering the input unit prices.

To complete the example, costs per 1,000 vehicles over both routes are given in Table 5 by consulting the appropriate operating cost tables. Costs resulting from curvature and speed changes are included (2). Multiplying these costs by the appropriate equivalent annual volumes for each vehicle type results in the total equivalent annual

TABLE 3

CALCULATION OF VEHICLE OPERATING COSTS USING COST TABULATIONS[a]

Section	Length (miles)	Percent Grade	Speed (mph)	Automobiles		Single-Unit Trucks		Combination Units	
				Cost per Mile	Cost	Cost per Mile	Cost	Cost per Mile	Cost
100-120	0.38	2.0	45	78.86	30.0	151.07	57.4	254.2	97
120-180	1.14	3.0	45	79.43	90.5	153.15	174.7	284.0	324
180-220	0.76	4.0	45	80.00	60.8	155.23	117.0	293.1	223
220-225	0.09	4.0	35	89.37	8.0	168.74	15.2	298.0	27
225-288	1.19	1.5	35	88.07	104.9	165.24	196.7	270.0	320
288-305	0.32	4.0	35	89.37	28.6	168.74	54.0	298.0	95
305-328	0.44	4.0	45	80.00	35.2	155.23	68.4	293.0	129
328-270	0.80	0.5	45	75.54	62.9	150.87	170.4	238.70	191
Subtotal					$421		$804		$1,406
Curve and speed change costs					42		106		370
Total operating cost					$463		$910		$1,776

[a]All costs are for 1,000 vehicles.

TABLE 4

HAND COMPUTATION OF AUTOMOBILE OPERATING COSTS ON TANGENT HIGHWAY, EXISTING ALIGNMENTS

Section	Length (miles)	Speed (mph)	Percent Gradient	Cost per 1,000 Vehicle-Miles (dollars)							Cost per 1,000 Vehicles ($)
				Fuel	Oil	Depreciation and Parts	Labor	Tires	Travel	Total	
1	2	3	4	5	6	7	8	9	10	11	2 x 11
100-120	0.38	45	2.0	15.80	1.65	21.10	3.28	2.50	34.40	78.73	29.95
120-180	1.14	45	3.0	16.10	1.65	21.10	3.28	2.55	34.40	79.08	90.10
180-220	0.76	45	4.0	16.62	1.65	21.10	3.28	3.05	34.40	80.10	60.90
220-225	0.09	35	4.0	15.20	1.65	22.20	2.92	2.78	44.40	89.15	8.03
225-228	1.19	35	1.5	13.90	1.65	22.20	2.92	2.50	44.40	87.57	104.20
228-305	0.32	35	4.0	15.20	1.65	22.20	2.92	2.78	44.40	89.15	28.55
305-328	0.44	45	4.0	16.62	1.65	21.10	3.28	3.05	34.40	80.10	35.20
328-370	0.80	45	0.5	15.50	1.65	21.10	3.28	2.37	34.40	78.30	62.60
Total cost per 1,000 vehicles											419.5

TABLE 5

SUMMARY OF ROAD USER COSTS

Vehicle	Equivalent Volume	Existing Route		Proposed Route	
		Dollars per 1,000 Vehicles	Total Cost (dollars)	Dollars per 1,000 Vehicles	Total Cost (dollars)
Passenger	425	463	1,720,000	372	1,385,000
Single-unit	50	910	400,000	743	325,000
Combination	25	1,776	390,000	1,320	290,000
Totals			2,510,000		2,000,000

operating costs. The annual operating cost savings for the proposed route ($510,000) can then be compared with the capital cost of the improvement. For a 20-year life and 5 percent rate of return these savings would justify a capital improvement of approximately $6.3 million.

CONCLUDING REMARKS

The purpose of introducing the example has been to illustrate application of the tables generated by the computer. However, it is important to note that this is not intended to be a computer model that is run every time a problem is encountered that requires the use of operating cost data. Basically, this program is intended to be used as a substitute for continuously updating such operating cost sources as the AASHO Red Book. In other words, it should be used to generate a series of tables covering a wide range of operating conditions (speed, grade, level of service) for a vehicle fleet that is typical for a particular region. Periodically, as either prices or composition of the vehicle fleet change, new sets of tables could be regenerated and used to assist in what would otherwise be a hand calculation of operating costs.

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An Approach to the Economic Evaluation of Urban Transportation Investments

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A conceptual framework for the economic evaluation of urban transportation investments is presented. It is suggested that urban transportation planners must be concerned with both the economic efficiency and the distributional efficiency of investment alternatives. The economic efficiency characteristics of transport investments are developed in terms of demand curves for accessibility and for environmental quality. Several measures of accessibility are reviewed and it is suggested that a community demand schedule for accessibility may be derived from models of the urban land market. It is suggested that demand schedules for environmental quality will have to be derived from regression analyses of urban property prices. It is demonstrated how the economic efficiency criterion may be modified to reflect distributional efficiency requirements. An approach is presented that is developed in terms of the accessibility gains to car owners and non-car owners.

•DURING RECENT YEARS there has been a growing disenchantment with the existing horizon-year type of urban transportation planning process. Many of the difficulties have arisen because of the inadequacies of the evaluation methodology embodied in this process. Two principal types of evaluation methodology have been proposed and used. The first group includes those that are based to some extent on welfare theory. Typical examples of this group are the frameworks proposed by Winch (1), Wohl and Martin (2), Beesley and Walters (3), and Rahmann and Davidson (4). The second group consists of those that have attempted to replace the concept of a competitive market by some form of rating scheme; it includes those reported by Hill (5), Schimpeler and Grecco (6), Falk (7), and others.

The principal difficulty with those methodologies based on economic theory is the reliance on market prices, or imputed market prices, for the measurement of benefits and costs. The second group is inadequate because of the lack of any sound conceptual basis. Rating scales possess many inherent deficiencies and the author has discussed some of the problems associated with their use in another context (8).

In spite of the shortcomings of welfare theory, it does provide a sound basis on which to erect an evaluation framework. Community preferences may find expression through mechanisms other than dollar-voting in the market, or even imputed dollar-voting. It is the purpose of this paper to advance an evaluation framework for urban transportation investments that the author believes will provide a broader approach to evaluation than those advanced by other authorities (1, 2, 3, 4).

EXISTING FRAMEWORKS

Winch (1) reported on one of the first attempts to apply the economic concepts of demand and supply schedules to highway investment analysis. He developed demand and supply curves for highway travel in terms of user costs of travel and the number of

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road vehicles passing a point on a highway link. The framework advanced by Winch assumes that the elasticities of demand for movement can be estimated and that there are no system effects of project investment. Winch does not attempt to account for the externalities associated with trip-making that are particularly important in urban area travel.

Wohl and Martin (2) have adapted the type of framework proposed by Winch to the economic evaluation of urban area road investments. Their framework is restricted to mutually exclusive investment alternatives, and their concentration on user benefits and costs restricts the application of their framework. In addition, their exclusion of consumer surplus from the benefits of road investments is not supported by the main body of economic thought.

Beesley and Walters (3) have also used an approach similar to that described by Winch. They have proposed that the objective of urban transportation system investment should be the maximization of the users' consumer surplus subject to constraints on those nonuser objectives that are influenced by the transportation system. Beesley and Walters emphasize the substitution and complementarity effects of road projects and attempt to incorporate these characteristics into their evaluation framework. They have also discussed the problems of urban amenity and the accommodation of various interest groups but have not provided a formal treatment of these two attributes of the problem.

The major features of these evaluation frameworks may be illustrated as shown in Figure 1. Hypothetical demand, DD, and supply SS, curves are shown in the diagram for two roads. The area WXYZ identifies the user benefits that may be assigned to the proposed road project. Also shown in Figure 1 is the users' marginal cost curve for increasing traffic volumes on the existing road. A number of investigators (9, 10) have noted the need for some form of congestion levy, in addition to the normal user taxes, in order to yield an efficient traffic volume on a roadway link. The magnitude of this congestion levy is given by AB.

A rather different approach has been proposed by Rahmann and Davidson (4). The principal difference in their evaluation framework from those mentioned previously is in their attempt to rationalize the modal investment problem. The previously mentioned frameworks are all restricted to the evaluation of road investments. The essence of the approach suggested by Rahmann and Davidson (4) is shown in Figure 2. In this diagram,

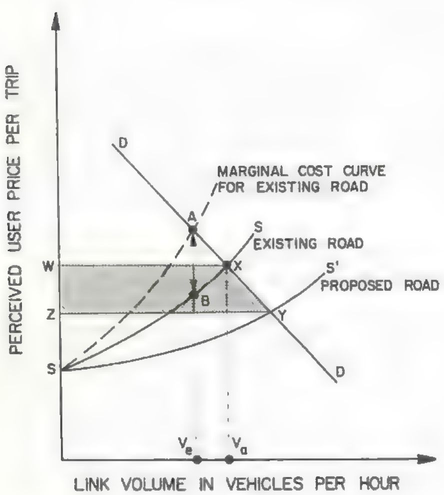

Figure 1. Basic structure of existing approaches to the economic evaluation of road investments.

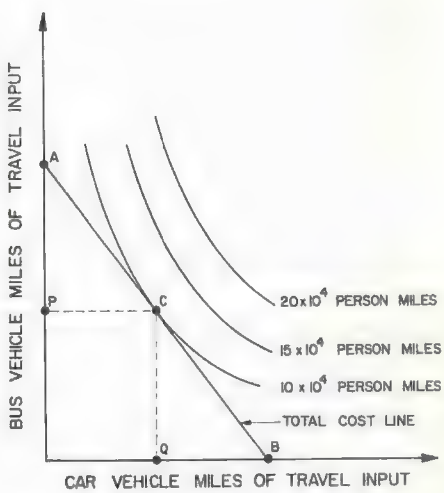

Figure 2. The Rahmann and Davidson approach to urban transportation investment analysis.

isoquants of transportation system output (person miles) are shown in terms of the combinations of car and bus mileage that would be required to yield these output levels. The line AB represents the total cost line and C yields the most efficient condition. That is, the community selects the combination of public and private transport at which the marginal rate of substitution of public for private transport equals the cost ratio as viewed by the community.

The framework proposed by Rahmann and Davidson provides a distinct improvement over those proposed previously. However, it is the author's opinion that this framework still fails to treat the nonuser dimensions of urban transportation investments adequately. Most of the issues associated with urban transportation investment in many urban areas involve conflicts between the provision of accessibility and the quality of the urban environment. None of the evaluation frameworks proposed to date provides a satisfactory mechanism for resolving these issues.

ELEMENTS OF AN EVALUATION FRAMEWORK

The principles of welfare economics and the methodology of systems engineering (11) indicate that the following sequence of activities must be performed in order to erect an economic evaluation framework:

1. Establish the community objectives (or preferences),
2. Identify the transportation system outputs that relate to each of these objectives,
3. Identify the strengths of the community objectives in the form of community willingness to pay for outputs, and
4. Identify a decision criterion for ranking alternative investment proposals and for establishing the optimal level of investment.

Each of these elements is explored in the following sections of this paper.

OBJECTIVES OF URBAN TRANSPORTATION INVESTMENT

It is appropriate to begin this discussion of the objectives of urban transportation investment by quoting from an essay by Marglin (12) on the objectives of water resource system investment.

> The prime objective of public water resource development is often stated as the maximization of national welfare. That this is a goal to be desired few would question; that it cannot be translated directly into operational criteria for system design, few would deny. Translation would require not only agreement on a definition for the deceptively simple phase "national welfare" but also some assurance that the defined concept is measurable.
>
> One possibility is to define national welfare as national income. The objective of system design then becomes maximization of the contribution of the system to national income. This definition is measurable, but it has implications for the meaning of national welfare that make us unwilling to accept it as a complete expression of the broad objective. Identifying national welfare with the size of the national income not only excludes non-economic dimensions of welfare but also implies either that society is totally indifferent as to the recipient of the income generated by river-development systems, or that a desirable distribution of gains will be made by measures unrelated to the way in which the system is designed.
>
> Social indifference to the distribution of income generated by the system suggests that the marginal social significance of income is the same regardless of who received it.

The broad goals of urban transportation investment might be identified as (a) maximizing the aggregate consumption of the community, and (b) assisting in the realization of an equitable real income distribution among members of the community. These broad goals reflect Marglin's statement that planners of public systems must be concerned with both economic or allocational efficiency and with distributional efficiency.

The concept of economic efficiency is usually defined in the following way. An allocation of resources to a system is said to be economically efficient if there is no other allocation of resources that would make anyone better off without making someone else worse off. The conditions that must be fulfilled to yield allocational efficiency within a system will be discussed later in this paper.

An allocation of resources to a system may be said to be efficient in the distributional sense if the distribution of real income corresponds to the distribution desired by the community. The question as to whether a particular urban-wide distribution of travel opportunities is efficient in the distributional sense is a value judgment that must find expression through the political process

The concept of distributional efficiency is illustrated by the following statement made by Thompson (13) in discussing socioeconomic segregation in cities in the United States:

> Simultaneously with the decline of mass transit, manufacturing, retailing, and other activities have been suburbanizing. With suburban densities far too low to support the extension of the lines of even a healthy mass transit system, the elderly, those financially unable to own a car, those unable to drive, and others, find that dependence on the central city mass transit system has narrowed their employment opportunities very appreciably. Clearly, growing affluence has led to greater mobility for most, but less mobility for a significant group, both in their roles as consumers and producers. A wide range of choice, the great virtue of the large city, is more the prerogative of some than others.

The goal of maximization of aggregate consumption may be divided into three groups of subgoals of objectives; they are (a) to maximize the aggregate accessibility provided by the system, (b) to maximize the aggregate environmental quality (as defined in 20) of the urban area that is related to transportation system outputs, and (c) to maximize the achievement of desirable long-term urban development patterns. These objectives suggest that a central problem of urban transportation investment analysis is to determine what kinds of urban development meet the aesthetic preferences of urban residents as well as their accessibility requirements. The orientation of investment implied by these objectives is quite different from the previous approaches to evaluation that have been concerned primarily with the evaluation of changes in movement impedance.

Experience with urban transportation investment in North American cities has demonstrated that, to a large extent, the objectives of accessibility and environmental quality are competitive. Much of the transportation investment has been concentrated in road facilities. These road facilities have allowed an increased penetration of urban land uses by motor vehicles that, in many instances, has decreased the environmental quality of these land uses.

A great deal of evidence is available (14) to demonstrate that the changes in the physical organization of urban areas have been a consequence of the changes in the costs of urban movement. Public investment in urban transportation facilities tends to reduce the costs of movement and thereby the costs of interaction between various activity centers of the urban area. However, urban land development is influenced by many other factors, and the third objective identified previously cannot be related exclusively to the accessibility objective. With the present state of knowledge regarding land development processes the formal characteristics of an evaluation framework must be restricted to a short-run equilibrium analysis. This assertion in no way minimizes the importance of this third objective. The overriding importance of this third objective has been stated very competently by Harris (15):

> The bland assumption of the economists that a competitive optimal allocation of resources coincides with a social optimum may lead to serious pitfalls. In part, these can be avoided by a consideration of externalities, but this will lead to a consideration of policies. This will happen because it will be discovered that the externalities of locational decisions are not covered in a system of economic rents, and consequently do not adequately influence the behavior of decision makers. There is also a deeper question of the same nature having to do with the development patterns and optimization over time. Even if present externalities are accounted for in the behavioral system and the related objective functions, the effects of current decisions are frozen in capital works. As time passes and conditions change, these decisions not only may be no longer optimal but they may generate new externalities as their effects are propagated through the system. It is almost certain that the institutional arrangements which might equate individual and social optimization at one point in time, would require drastic modifications to equate current individual optimization with long run social optimization.
>
> As capital is not instantaneously convertible from one use to another, dynamic development patterns depend not only on instantaneous pressures but upon the whole history of the system.

The position taken for the purposes of this paper is that formal evaluation of transportation investment proposals must be restricted to the objectives of environmental quality and accessibility. The third objective must be realized through other types of policy decision.

URBAN TRANSPORTATION SYSTEM OUTPUTS

The models of urban development that have been developed to date have illustrated that, at least for North American conditions, location or accessibility is the dominant factor in determining the uses of land and the intensities of uses. One definition of accessibility is that derived from the gravity model, given by

$$ACC_i = \sum_{j=1}^{n} A_j \cdot f(d_{ij}) \tag{1}$$

where

ACC_i = the accessibility of zone i relative to the n other zones of the urban region,
A_j = a measure of the attractiveness of these other zones, and
$f(d_{ij})$ = a measure of the travel impedence between zones i and j.

Equation 1 demonstrates that accessibility is a relative quality that accrues to a parcel of land by virtue of its relationship to other parcels of land and the quality, or level of service, provided by the transportation system. It must be recognized that the accessibility measure defined in Eq. 1 is only one possible measure. Little direct systematic evidence has been assembled to demonstrate that this accessibility characteristic is truly the fundamental characteristic of a transportation network that the community is willing to pay for.

Schneider (16) has proposed a formulation of accessibility that may prove to be a more realistic measure of this quality of an urban zone. He has developed the following expression for travel:

$$\frac{dV}{dR} = cI \tag{2}$$

where

V = number of trips to and from a zone,
R = an undefined characteristic of a zone that attracts trips to it,
I = $\int FdR$, called the access integral of a point,
F = a function of the separation between zones,
c = constant of proportionality = $V_T/\int IdR$, and
V_T = total trips in the region.

Equation 2 indicates that the trip density at a point per unit of attractiveness is proportional to the accessibility of the point.

Schneider then goes on to develop the following expression for change in the development of a zone:

$$R_f = R_F \cdot R_a I/(J - R_F I) \tag{3}$$

where

R = $R_a + R_f$,
R_a = some trip-attracting characteristic of a zone that is proportional to its land area,
R_f = some trip-attracting characteristic of a zone that is proportional to its development,
R_F = some characteristic that is proportional to the total floor area in the region, and
J = $\int IdR$.

TABLE 1

PEDESTRIAN DELAY AND NOISE LEVELS CAUSED BY VARIOUS TRAFFIC FLOWS

Traffic Flow (vehicles per hour)		Pedestrians Delayed (percent)	Average Delay to All Pedestrians (second)	Approximate Noise Level, dBa[a]	
All Vehicles	Heavy Vehicles			Mean	Climate[b]
50	5-10	6-7	<1	51	49-60
100	10-20	11-13	<1	53	49-62
150	15-30	15-19	<1	55	51-64
200	20-40	20-24	<1	56	51-65
250	25-50	24-29	<1	58	52-67
300	30-60	28-34	0.8-1.2	59	53-69
400	40-80	35-42	1.0-1.7	61	55-71
500	50-100	43-50	1.3-2.2	63	57-73
750	75-150	56-65	2.2-3.8	67	61-75
1,000	100-200	67-75	3.3-5.9	69	64-77

[a]dBa = decibels above reference noise, adjusted. [b]10 to 90 percent of whole time.

Equation 3 may provide the required link between the output of the transportation system and the willingness to pay for this output.

Another interesting approach to the characterization of the accessibility of points in an urban region is that developed by Rassam and Ellis (17). They have shown that the travel impedances between points in an urban region can be estimated analytically, given certain assumptions about the geographic distribution of speed within an urban area. This approach may also provide an important link between the transportation system output and the willingness to pay for this output. The average speed on the links of a highway network has been used in several studies (18, 19) to impute the user willingness to pay for output.

The definition and measurement of environmental quality has not received as much attention as accessibility. The Buchanan report (20) and other studies in Great Britain (21) provide the major sources of information. Pendakur and Brown (22) have explored the environmental quality of a suburban shopping street in Vancouver using some of the concepts developed in the earlier studies.

It is generally agreed that the two major factors influencing the environmental quality of an urban zone are (a) the volume of vehicles using a transportation network link (either transit vehicles on separate rights-of-way on the street or motor vehicles), and (b) the visual intrusion of parked transport vehicles and their rights-of-way. The characterization of the environmental impacts of motor vehicles is discussed first.

Motor vehicles affect the environmental quality through their emission of noise, exhaust fumes, and vibration and through their interference with pedestrian circulation and safety. Table 1 gives certain information obtained in Great Britain for the delays to pedestrians and the noise levels caused by various vehicle volumes. Figure 3 shows a relationship developed by the Wilson Committee (23) in Great Britain that relates the mean noise level to traffic volume. In the absence of additional information on environmental quality, the average vehicle volume on a road link would seem to provide the transport system output that relates most directly to environmental quality.

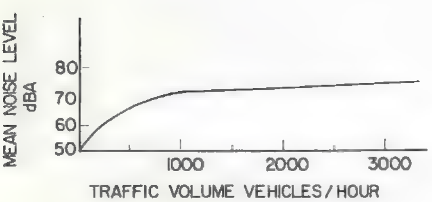

Figure 3. Mean noise level versus traffic volume.

Parked vehicles are considered to detract from environmental quality through their visual intrusion and their influence on pedestrian safety. The provision of parking facilities for motor vehicles that provide adequate standards of civic design usually involves significant expenditures and represents an important dimension of the costs of providing environmental quality.

A comprehensive measure of environmental quality would require a rationale for weighting

each of the dimensions of environmental quality to yield a single index. However, insufficient evidence is available to allow such an index to be derived. The following discussion proceeds on the assumption that a unique measure of environmental quality will be derived in the short run.

The environmental impacts of transportation technologies other than motor vehicles also include noise and visual intrusion. These characteristics vary greatly with the type of technology and cannot be summarized easily. Figure 4 is an example of the type of information that is available for other modes of transport (24).

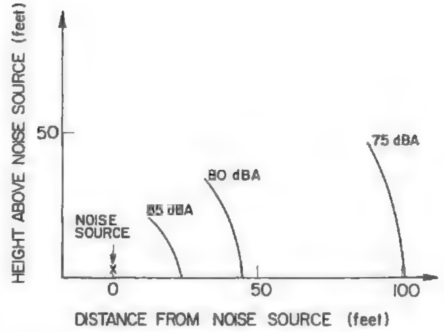

Figure 4. Noise intensity generated by a typical steel-wheeled rapid transit system.

COMMUNITY WILLINGNESS TO PAY FOR OUTPUTS

The community demand schedule is the economic concept that is available for expressing the community willingness to pay for various levels of system output. Figure 5 shows the demand curves that are of interest to the evaluation framework developed in this paper. These demand curves indicate that willingness to pay consists of a market value plus the triangle called the consumer surplus. The consumer surplus is usually defined as the difference between the maximum amount consumers are willing to pay for a specified quantity of a good rather than go without it and the value of the given quantity of the good at its competitive market price.

If the urban land market were perfectly competitive, and if accessibility and environmental quality were the major characteristics of a parcel of land that buyers were willing to pay for, then community demand curves for accessibility and environmental quality could be derived directly. These demand curves must be derived by indirect means, and it is the purpose of this section of the paper to explore possible ways of deriving community demand curves.

A number of studies have been made of urban land values, but none of these studies have related land values to reasonable measures of accessibility. Kain (25) has assumed a linear relation between land values and straight-line distance from the CBD, whereas Berry, Simmons, and Tennant (26) have observed a negative exponential relationship between land values and distance from the CBD. These broad relationships do not reflect adequately the many local peaks in land values that occur in major urban regions and provide a poor basis for the derivation of community demand curves. Theoretical frameworks of the type developed by Wingo (27) and Alonso (28) appear to provide the most promising approach to the derivation of a demand curve. The basic structure of the framework proposed by Wingo is reviewed briefly in the following to demonstrate one possible approach.

Wingo (27) has isolated the transportation function shown in Figure 6a as the key feature of an urban transportation system that influences the distribution of households in an urban region. Wingo has then shown how this transportation function may be used to derive a spatial structure of position

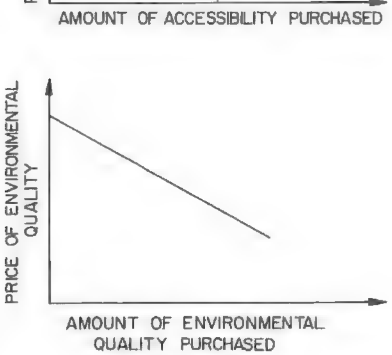

Figure 5. Community demand curves required by the evaluation framework.

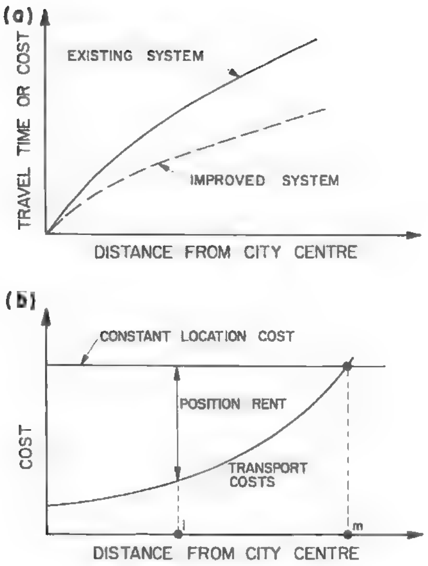

Figure 6. Curves showing (a) the transportation function and (b) the spatial structure of position rents.

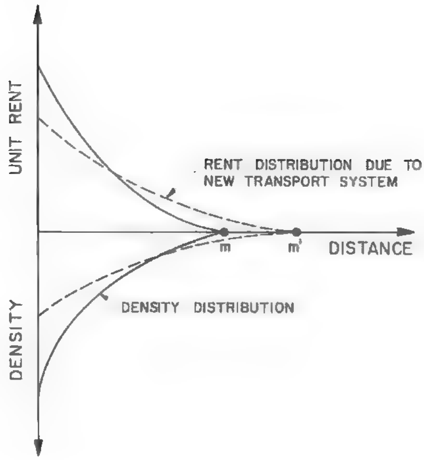

Figure 7. Unit rent and density profiles with distance.

rents, as shown in Figure 6b. The notion embodied in Figure 6b is that the householder located at i enjoys a premium in transportation costs with respect to a household located at the margin. This locational premium invites competition from all households located at a greater distance than i, because a household at the margin can offer a position rent for i equal to the difference in transportation costs, R_i. In this way, a locational equilibrium is established where each household's locational costs are constant. Wingo has then demonstrated how density and unit rent profiles of the type shown in Figure 7 may be derived from certain assumptions about space consumption and the position rent relation of Figure 6b. Changes in the density and unit rent profiles resulting from changes in the transportation function are shown by the broken lines in Figure 7 and 6a respectively.

Little empirical evidence is available to allow the rent surfaces to be defined. However, this theoretical approach or the present attempts at modeling the housing market (29, 30) should provide a means for deriving a community demand function for accessibility.

With the present state of knowledge regarding the measurement and evaluation of environmental quality, it would appear that a community demand curve will have to be derived by a regression analysis of property values. However, it has already been noted that the urban property market is influenced by a large number of factors other than accessibility and environmental quality.

A DECISION CRITERION FOR HORIZON-YEAR SYSTEMS

A decision criterion is required that will allow the most efficient system to be identified. The criterion presented in this section has been developed by Marglin (12, 31) for water resource systems. The decision criterion proposed by Marglin represents a modification of the Pareto optimality condition and is defined in the following paragraphs.

A proposed horizon-year urban transportation system A1 is economically more efficient than a system A2 if those affected by A1 are willing to pay those affected by A2 a sum sufficient to persuade them to agree to the construction of A1. Willingness to pay for a system may be subdivided into those who are made better off and those who are made worse off by a system A as expressed by the following equation:

$$W(A) = E(A) - C(A) \tag{4}$$

where

$W(A)$ = aggregate willingness to pay for system A,
$E(A)$ = willingness to pay of those who benefit from system A rather than have no system at all, and
$C(A)$ = willingness to pay of those who disbenefit from system A not to have the system at all.

Marglin (12) has pointed out that the decision criterion of Eq. 4 will provide a transitive ordering of systems only if the amount that the beneficiaries of one system are willing to accept as compensation to do without their project is equal to the amount that they are willing to offer as compensation to the beneficiaries of other systems to persuade them to do without their projects.

A production function may be defined as

$$f(x_1, x_2, \ldots, x_i, \ldots, x_m, y_1, y_2, \ldots, y_j, \ldots, y_n) = 0 \tag{5}$$

where

x_i = the quantities of factors used in production, $i = 1, \ldots, m$; and
y_j = the quantities of goods produced, $j = 1, \ldots, n$.

Equation 4 may be rewritten to incorporate the production function terminology of Eq. 5 as follows:

$$W(\vec{x}, \vec{y}) = E(\vec{y}) - C(\vec{x}) \tag{6}$$

where

$\vec{x}$ = the vector of input variables, and

$\vec{y}$ = the vector of output variables.

The decision criterion becomes the selection of the system with the maximum value of $W(\vec{x}, \vec{y})$ subject to the constraint that it is a member of the production function. If Eqs. 5 and 6 are differentiable, then the following Lagrangian function may be defined:

$$L(\vec{x}, \vec{y}) = W(\vec{x}, \vec{y}) + \lambda f(\vec{x}, \vec{y}) \tag{7}$$

where λ = the undetermined Lagrangian multiplier.

The maximum conditions for Eq. 7 are given by

$$\frac{\partial w}{\partial x_i} = -\lambda \cdot \partial f/\partial x_i \text{ for } i = 1, \ldots, m \tag{8a}$$

and

$$\frac{\partial w}{\partial y_j} = -\lambda \cdot \partial f/\partial y_j \text{ for } j = 1, \ldots, n \tag{8b}$$

If Eq. 8a is divided by Eq. 8b, the following expressions may be obtained:

$$\frac{\partial w}{\partial x_i}\Big/\frac{\partial w}{\partial y_j} = \frac{\partial f}{\partial x_i}\Big/\frac{\partial f}{\partial y_j} \tag{9a}$$

$$\frac{\partial w}{\partial x_i}\Big/\frac{\partial w}{\partial x_h} = \frac{\partial f}{\partial x_i}\Big/\frac{\partial f}{\partial x_h} \tag{9b}$$

$$\frac{\partial w}{\partial y_j}\Big/\frac{\partial w}{\partial y_k} = \frac{\partial f}{\partial y_j}\Big/\frac{\partial f}{\partial y_k} \tag{9c}$$

The production function constraint is $f(\vec{x}, \vec{y}) = 0$ and this yields

$$\frac{\partial f}{\partial x_i} \bigg/ \frac{\partial f}{\partial y_j} = -\partial y_j / \partial x_i \tag{10a}$$

$$\frac{\partial f}{\partial x_i} \bigg/ \frac{\partial f}{\partial x_h} = -\partial x_h / \partial x_i \tag{10b}$$

$$\frac{\partial f}{\partial y_j} \bigg/ \frac{\partial f}{\partial y_k} = -\partial y_k / \partial y_i \tag{10c}$$

Equation sets 9 and 10 yield the necessary conditions for an input/output vector that maximizes Eq. 8; these conditions are

$$\frac{\partial w}{\partial x_i} \bigg/ \frac{\partial w}{\partial y_j} = -\partial y_j / \partial x_i \tag{11a}$$

$$\frac{\partial w}{\partial x_i} \bigg/ \frac{\partial w}{\partial x_h} = -\partial x_h / \partial x_i \tag{11b}$$

$$\frac{\partial w}{\partial y_j} \bigg/ \frac{\partial w}{\partial y_k} = -\partial y_k / \partial y_j \tag{11c}$$

The three conditions described may be interpreted in several ways. Equation 11a identifies the condition that the ratio of the marginal cost of the ith input to the marginal benefit of the jth output must be equal to the marginal productivity of the ith input when devoted to the jth output. Equation 11b states that the ratio of the marginal cost of the ith input to the marginal cost of the hth input should be equal to the marginal rate of substitution of the hth input for the ith input. The condition identified in Eq. 11c states that the ratio of the marginal benefit of the jth output to the marginal benefit of the kth output should be equal to the marginal rate of transformation of output k for output j. Equation 11a also implies that the marginal benefits equal marginal costs.

If the community demand curve is represented as a function $y_j(p)$ of the price p, willingness to pay is given by

$$E(y_j) = \int_o^{y_j} D(\eta) d\eta \tag{12}$$

where

η = a dummy variable of integration, and
$D(\eta)$ = the inverse of the function $y_j(p)$.

The benefit of each output y_j is the willingness to pay for that output, and the aggregate benefits are given by the sum of the benefits of each output:

$$E(y) = \sum_{j=1}^{n} \int_o^{y_j} D(\eta) d\eta \tag{13}$$

providing that the willingness to pay for each output is independent of the quantities of other outputs provided by the system.

When construction expenditures and benefits are spread over many time periods, the following decision criterion may be defined:

$$W(A) = \sum_{q=1}^{Q} v_q \left[E_q(y_{jq}) - M_q(x_{iq}) - k_q(x_{iq})\right] \tag{14}$$

where v_q = the present value factor applicable to the demand period q, which is given by

$$v_q = \left[1 - (1+i)^{-T/Q}\right] \Big/ \left[i(1+i)^{(q-1)T/Q}\right] \tag{15}$$

and where

q = 1, 2, . . ., Q, and is the particular time period,
i = discount rate,
T = the economic life of the system in years,
$E_q(y_{jq})$ = the annual benefits in period q as a function of the outputs in period q,
$M_q(x_{iq})$ = the continuing (maintenance, etc.) costs during period q, and
$K_q(x_{iq})$ = the capital cost during period q.

The marginal conditions for the maximization of Eq. 14 have been identified in Eq. 11a, which yields from Eq. 14 the following:

$$\sum_{q=1}^{Q} v_q D_{jq}(y_{jq}) \partial y_{jq}/\partial x_i = \sum_{q=1}^{Q} v_q (\partial M_q/\partial x_i + \partial K_q/\partial x_i) \tag{16}$$

Equation 16 states that the marginal willingness to pay for output in period q rather than go without $[D_{jq}(y_{jq})]$ times the marginal productivity in period q of the i th input when devoted to the j th output $(\partial y_{jq}/\partial x_i)$ is equal to the sum of the present value of continuing and capital marginal costs.

Equation 16 may be written in the simple notation of the following equation:

$$\sum_{q=1}^{Q} v_q MVP_q(x_i) = \sum_{q=1}^{Q} v_q \left[MM_q(x_i) + MK_q(x_i)\right] \tag{17}$$

where

$MVP_q(x_i)$ = the marginal value (revenue) product (i.e., marginal annual benefit) in period q from an extra unit of input x_i,
= the partial derivative $D_{jq}(y_{jq})\partial y_{jq}/\partial x_i$,
$MM_q(x_i)$ = the marginal annual continuing costs, and
$MK_q(x_i)$ = the marginal capital cost.

If the time horizon notation is suppressed and Eq. 16 is divided by $\partial y_j/\partial x_i$, the following expression is obtained:

$$D_j(y_j) = \frac{\partial M}{\partial x_i} \cdot \frac{\partial x_i}{\partial t_j} + \frac{\partial K}{\partial x_i} \cdot \frac{\partial x_i}{\partial y_j} \tag{18}$$

which may be restated as

$$ME(y_j) = MM(y_j) + MK(y_j) \tag{19}$$

This equation states that the marginal willingness to pay for the output y_j is the rate at which the recipient of outputs is willing to substitute money for the output, which is equal to the sum of the marginal continuing and maintenance costs representing the rate at which money can be transformed into output by the construction and operation of the system.

If it is assumed that the community demand schedules for accessibility and environmental quality have been defined, and if it is further assumed that the financial inputs to the transportation system are the continuing and capital expenditures throughout the

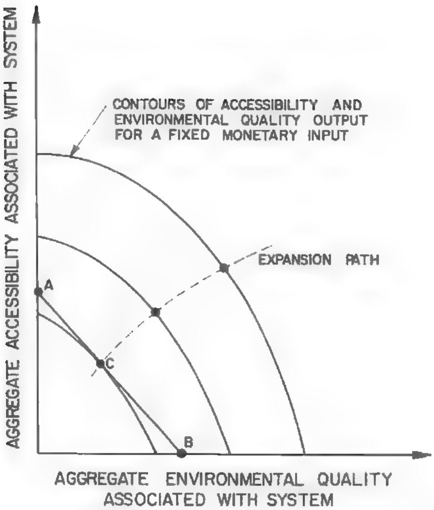

Figure 8. Input-output relations and the expansion path.

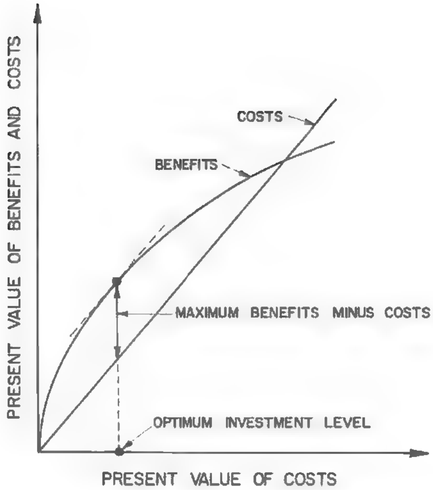

Figure 9. Determination of the optimum investment level.

period T, then the pertinent economic characteristics of alternative systems may be expressed as shown in Figure 8. This diagram shows the combinations of accessibility and environmental quality that can be achieved for a fixed monetary input. That is, each transformation function represents a contour of output for a fixed monetary input. A price line AB can also be shown in Figure 8, at least conceptually, that represents the combinations of accessibility and environmental quality that are of constant value.

The equilibrium or efficiency condition is given by the point of tangency between the price line and the transformation function contour. That is, point C shows the best combination of outputs that can be achieved for a fixed input. In fact, the locus of the points of tangency may be established for increasing monetary inputs as shown in Figure 8. Figure 9 may be constructed from Figure 8 to show the net present value of benefits for each input level. The optimum investment level may be determined from Figure 9 at the point at which the benefit and cost curves are parallel. This is the condition specified in Eq. 11a. An alternate approach to this same problem is shown in Figure 10, in which the community indifference curve is used to establish the equilibrium condition at C.

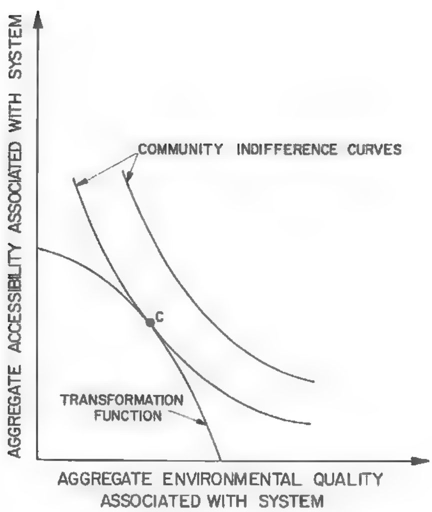

Figure 10. Identification of equilibrium condition using the community indifference curve.

In practice it may be difficult to establish the price line of Figure 8 or the community indifference curve of Figure 10. This problem may be resolved by using one of the following criteria:

1. Maximize the aggregate accessibility of the system subject to a constraint on the aggregate level of environmental quality, or
2. Maximize the aggregate environmental quality of the system subject to a constraint on the aggregate level of accessibility.

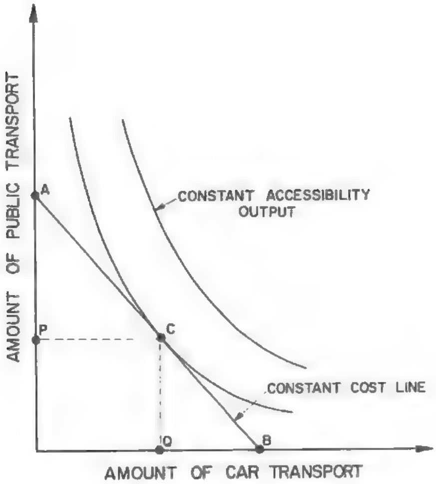

Figure 11. Accessibility isoquants for various input combinations and input combinations yielding a constant cost.

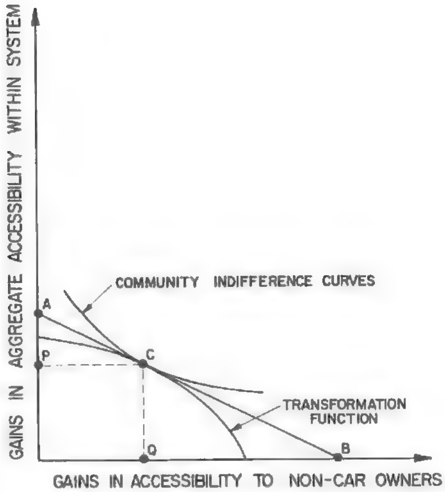

Figure 12. The analysis of distributional efficiency.

An alternative view of the problem may be developed if it is assumed that the inputs to the system are limited to public transport facilities and private-car-oriented facilities. A relationship of the type shown in Figure 11 may be developed that shows isoquants of accessibility output for various combinations of public transport and road facilities. A similar diagram for isoquants of environmental quality output could be prepared as well. If the costs of the public transport and road facilities are specified, then the constant cost line AB may be established and used to identify the optimum mix of facilities at C, which is similar to the approach suggested by Rahmann and Davidson (4).

Modification of the Allocational Efficiency Criterion

The decision criteria examined have been concerned with identifying the conditions that would yield economically efficient transportation investments. The allocational efficiency criterion must be modified to reflect the second goal of urban transportation investment, which is concerned with distributional efficiency.

It is useful to recall that a fundamental assumption of welfare theory is that the marginal utility of income is constant and equal for all members of the community. It was pointed out earlier that distributional efficiency must be appraised relative to a disaggregated view of an urban region which recognizes the irrational nature of the given assumption. For the purposes of this paper, it is assumed that urban households may be classified into car-owning (CO) and non-car-owning (NCO) households. It is further assumed that NCO households tend to be segregated geographically and that these households lack adequate urban travel opportunities. The distributional efficiency of alternative urban transportation investment proposals may be examined in terms of Figure 12.

In Figure 12 the gains in aggregate accessibility of an urban region are plotted along the ordinate and the gains in NCO zones accessibility are plotted along the abscissa. Community indifference curves may be plotted in Figure 12 showing the relative weights that the community places on these two objectives. The indifference curves shown in Figure 12 suggest that a premium is placed on the gains in accessibility to NCO zones relative to aggregate accessibility. A transformation function may also be plotted in Figure 12 illustrating the boundary of feasible transportation investments with respect to their relative contributions to aggregate accessibility and to the accessibility of NCO

zones. The equilibrium condition is given by point C, which is the point of tangency between the transformation function and an indifference curve. At point C the slope of both curves is equal to the slope of AB, which implies that the marginal rate of transformation between aggregate and NCO accessibility and the marginal premium on NCO accessibility relative to aggregate accessibility are equal. The program of investment represented by point C will contribute OP to aggregate accessibility in the region and OQ to the accessibility of NCO zones. A similar approach could be identified for the treatment of environmental quality.

A decision criterion may also be subjected to constraints on the minimum levels of accessibility and environmental quality that should exist within individual zones. The decision criterion then becomes the maximization of the weighted contributions to aggregate consumption subject to constraints on zonal accessibility and environmental quality.

SUMMARY AND CONCLUSIONS

Existing approaches to the economic evaluation of urban transportation investment proposals assume that the principal output of a transportation system that gives rise to benefits is the volume of vehicles passing along links of a network. This paper outlines an evaluation framework in terms of two broader outputs: accessibility and environmental quality.

The paper suggests that urban transportation planners must be concerned with both the economic efficiency and the distributional efficiency of investment alternatives. The goal of economic efficiency is developed in terms of the following objectives: (a) the maximization of aggregate accessibility, and (b) the maximization of aggregate environmental quality.

Several measures of accessibility are reviewed, but insufficient evidence is available to support the choice of one of these measures. The few studies of environmental quality that have been performed to date suggest that link traffic volumes are the best system outputs to relate to the environmental quality objective.

The paper suggests that the derivation of a community demand schedule for accessibility will have to be derived from models of the urban land market that have been calibrated for a given region. Community demand schedules for environmental quality will have to be derived from regression analyses of urban property prices.

A decision criterion for allocational efficiency is presented that is derived from welfare theory principles. The paper demonstrates how this efficiency criterion may be modified to reflect distributional efficiency.

The framework outlined provides a conceptual basis for the economic evaluation of urban transportation investment proposals. Empirical evidence must now be assembled to make this framework operational.

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An Investment Approach Toward Developing Priorities in Transportation Planning

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Chicago Area Transportation Study

This paper discusses the development of priorities in transportation planning as a problem in investment planning or capital budgeting. Determination of a construction program for a regional freeway network is used to illustrate the approach. This analysis is carried out with two mathematical programming formulations; one formulation permits early acquisition of right-of-way, and the other does not. In these formulations, the objective is to order construction of segments of the network so that the net user benefits of these freeway segments are maximized. The maximization of this objective is subject to several constraints. Expenditures on the freeway segments are limited by the budget allocated for that purpose, and the entire network must be completed by a particular date. The results of the analysis permit establishment of project priorities and of a construction program for completing the network in a particular length of time. A significant advantage of the use of mathematical programming techniques in this investigation is the ease with which sensitivity analyses can be accomplished; the impact of alternate budgets and varying lengths of time to construct the facilities can be readily determined.

•ONE of the more critical aspects of the transportation planning process is the determination of construction priorities for the recommended plan. If a transportation plan is to be effectively implemented, a program for construction must be prepared. Specific guidelines on when to start individual projects are needed to ensure completion of the plan by the design year. The development of such a program requires more than subjective rating of individual projects. Even some analytic measure of each individual project's worth will alone not be sufficient. Although these measures are needed for an analysis, they do not take into account how the plan will be financed; therefore, the funding available for new construction must also be examined.

These two elements—the worth of individual projects and the financing available for their construction—are the basic inputs that must be investigated to determine when individual projects should be constructed. But another important factor must be considered; this factor is time, because all but the very simplest transportation plans will require a number of years for completion. The worth of a project usually changes with time when the project is opened to serve traffic. Furthermore, the flow of funds for construction may fluctuate from year to year during the period of time needed to implement the plan.

Thus, the objective for a program of construction should be to take advantage of these changes in the worth of individual projects over time, and to schedule individual projects so as to maximize the total benefit of all projects in the plan. This is subject, of course, to the restrictions imposed by the flow of funds for construction purposes. Consequently, the analysis to evaluate alternate construction programs described in this paper was developed from the following objectives:

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1. Maximization of user return through early construction of heavily used facilities; and

2. Feasibility of financing—the projects scheduled in any budgeting period cannot exceed the funds available for that period.

The above framework is analogous to an investment planning, or capital budgeting, study (1). This paper adopts investment planning concepts and applies them to a typical problem in regional transportation studies, the determination of a construction program for a regional freeway system. Implicit in this approach is the assumption that the flow of available funds can be predicted with sufficient accuracy to make the resultant program attainable and compatible with the previously stated objectives of construction programming. Also, it must be emphasized that the evaluation of the proposed facilities has already taken place prior to this programming analysis. Improvements to the network have already been justified through the Chicago Area Transportation Study (CATS) evaluation of the entire transportation system. The question here is not whether a facility should be built, but rather when it should be built.

PROBLEM DESCRIPTION

The Final Report of the Chicago Area Transportation Study (2) proposed a transportation plan for the region that has been accepted by the Northeastern Illinois Planning Commission and various operating and government agencies in the Chicago metropolitan area. A regional freeway network, which is now being built, is an integral part of the proposed highway plan. Figure 1 shows the corridors making up this network and the staging of construction recommended in the CATS Final Report. The first stage included all committed freeway facilities in the region as of 1960. This portion of the freeway network is presently near completion, and work is now being started on several portions of the second stage. Figure 2 shows the current status of the network.

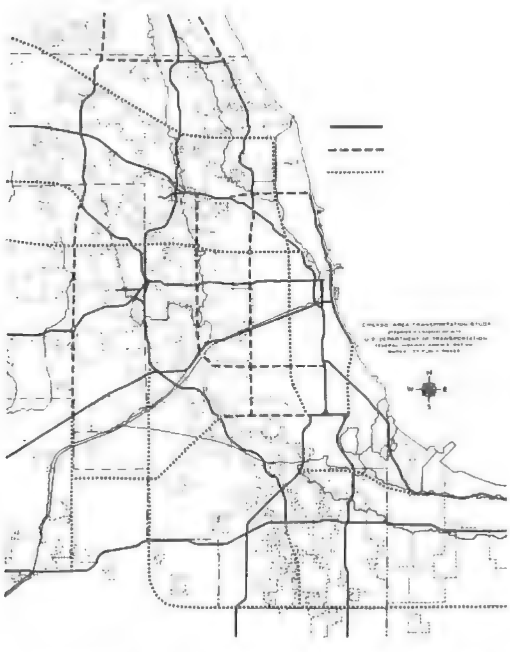

Figure 1. CATS proposed freeway plan and recommended staging of construction.

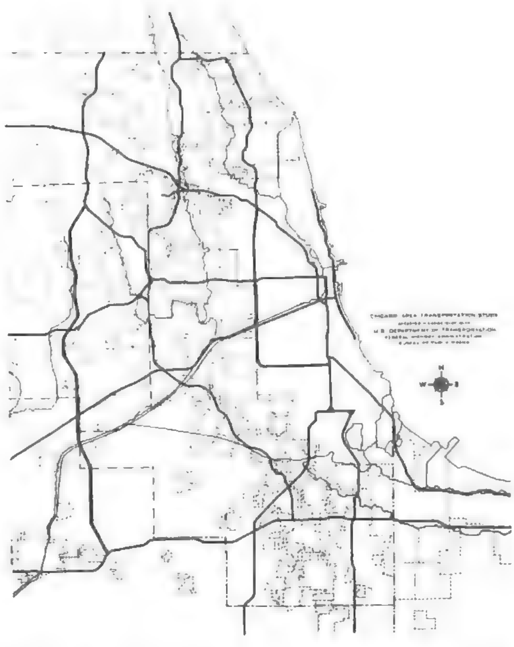

Figure 2. Existing and committed freeways in the Chicago area.

Because location studies for most of the remaining facilities in the second stage of the plan and part of the facilities in the third stage are now in progress or about to start, the determination of a preliminary construction program for these segments is of prime importance. The portion of the network for which the construction program is to be developed is shown in Figure 3. These routes are intended to supplement the existing Interstate and primary freeway network in the region and to provide improved access to the suburban areas they serve.

Figure 3. Existing and committed freeways plus network for program development.

The major reason for these facilities being included in the plan is clear. The suburban Chicago metropolitan area is undergoing rapid development and the increase in the amount of travel generated in these areas will be dramatic. Unfortunately, the costs associated with construction of these supplemental freeways are also expected to rise. Of particular importance is the expected increase in the cost of right-of-way. Land that is presently at a low level of development will be heavily utilized within several years and right-of-way costs may become prohibitive. Therefore, in addition to the problem of scheduling construction of these supplemental freeway facilities, there is timing of the right-of-way purchases to consider. The trade-off between funds going for early acquisition of right-of-way and funds going for actual construction of facilities must be investigated.

There are several reasons why this problem and many similar problems dealing with the scheduling of improvements to transportation facilities should be viewed as investment planning problems. First, a large number of decisions on alternate courses of action must be made at different points in time; in this case, alternate segments of the network may be constructed, or different parcels of right-of-way may be purchased. Second, the absolute and relative worth of these alternate courses of action change over time. The return on each project in the example being considered varies with changing travel demands, the changing cost of constructing the facility, and the increasingly expensive right-of-way. Finally, the flow of funds for investment is reasonably predictable over time and is independent of the selection of a particular course of action. The funds are committed over a period of years for completion of the network.

In this paper, the development of two mathematical programming formulations designed to analyze the problem of scheduling construction of these supplemental freeways is presented. The initial mathematical program does not include the possibility of early acquisition of right-of-way, whereas the second formulation considers this potential course of action. This latter mathematical program balances the benefits resulting from advance acquisition of right-of-way against the benefits resulting from actual construction. Thus, the second formulation is a logical extension of the initial mathematical program.

DEVELOPMENT OF INITIAL MATHEMATICAL PROGRAM

Mathematical programming was selected as the tool for analyzing this problem (3). As a first step, the time between the present and the future completion date of the net-

work is divided into n equal time intervals. Each time interval corresponds to a time period with a definite budget established for the construction of supplemental freeway facilities. For this problem, five 2-year budgeting periods were used. The next step is to divide the network into m segments. The network is sectioned so that each individual segment is a major part of the completed network and yet still can be constructed within a single budgeting period. The 11 selected segments of the supplemental freeway network are shown in Figure 4.

Figure 4. Supplemental freeway network segments.

Initially, the problem was formulated as a mathematical program without considering early acquisition of right-of-way. This formulation was further idealized by assuming that all benefits created through construction of a freeway segment are accountable; all future benefits can be properly appraised and included in the analysis. Like all mathematical programs, this formulation consists of three parts:

1. The choice variables, i.e., variables corresponding to construction of freeway segments in different budgeting periods;
2. The objective function, i.e., a mathematical expression that computes the benefits associated with a construction program; and
3. The constraints, i.e., relationships among choice variables that limit the construction programs that may be considered.

Mathematically, the objective function may be stated as follows:

$$\text{maximize} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=j+1}^{\infty} B_{ik} Y_{ij}$$

where
Y_{ij} = 0 if segment i of the network is not constructed in budgeting peroid j,
Y_{ij} = 1 if segment i of the network is constructed in budgeting period j, and
B_{ik} = the present worth of the net benefit (user return minus segment costs) in budgeting period k derived from construction of segment i in a previous budgeting period.

Variable Y_{ij} is subject to the following constraints:

1. $\sum_{i=1}^{m} tc_{ij} Y_{ij} \le C_j \quad \text{if } 1 \le j \le n$

2. $\sum_{j=1}^{n} Y_{ij} = 1 \qquad \text{if } 1 \le i \le m$

3. $Y_{ij} = 0 \text{ or } 1$

where

tc_{ij} = the total construction and right-of-way costs of segment i if built in budgeting period j, and

C_j = the budget allowed for completion of the network in budgeting period j.

The first constraint ensures that the sum of all expenditures in a budgeting period is less than the funds budgeted for that period. The second and third constraints together require all freeway segments to be built by the n th budgeting period.

This formulation assumes that a budget surplus cannot be carried over to the next budgeting period. If this is not the case, the first constraint can be replaced by the following constraint, which allows budget transfers to a later budgeting period:

$$\sum_{i=1}^{m} tc_{ij} Y_{ij} + S_j = C_j + (I + 1)S_{j-1} \text{ if } 1 \leq j \leq n$$

where

S_j = the budget surplus in budgeting period j, and

I = the interest rate per budgeting period for a budget surplus.

This mathematical program is an integer linear programming problem, a type of problem that is notoriously intractable. Fortunately, this problem can be solved fairly simply, disregarding the summation of net benefits, B_{ik}, to infinity for the present, because all integer solutions can be generated with exactly m of Y_{ij} equal to one (4). Thus, solution of the problem through conventional linear programming techniques can be accomplished by restricting the number of Y_{ij} in the solution. This restriction can be handled by either limited-basis entry or post-optimal procedures.

DETERMINATION OF A FREEWAY SEGMENT'S BENEFIT

The definition and measurement of all benefits and diseconomies resulting from freeway construction have been debated for some time, yet there is common agreement that the evaluation of proposed major highway facilities must be as broadly based as possible. However, in implementing a plan that has been broadly evaluated, a more limited base for making a decision about the priorities of constructing segments or purchasing rights-of-way is sufficient. Thus, in employing only changes in user costs to determine the return on individual freeway segments, the intent is not to provide a warrant for construction of the facility, but rather to assess the relative merits of the alternate freeway segments. Again, the question is not whether a facility should be built, but when it should be built.

In defining user benefits, it is assumed that the future demand for travel in the corridor associated with a particular supplemental freeway segment does not depend on whether the freeway is built. Furthermore, it is also assumed that over time the change in this demand is independent of when the facility is constructed. Within each segment's corridor there exists a certain amount of traffic that would be diverted to a freeway facility in the corridor. If this facility were not built, this traffic would remain in the segment's corridor but would travel over the corridor's other arterial facilities. The user benefit for each freeway segment is then defined as the difference between the cost of operation on a freeway and the cost of operation on an arterial without a freeway in the corridor to handle the divertible traffic.

To calculate the benefits from these freeway segments, existing traffic assignments over the CATS final highway plan were used to provide an estimate of 1985 travel on the proposed supplemental freeway facilities. Each of these estimates was assumed to equal the vehicle-miles of divertible traffic in a freeway segment's corridor. From these estimates, the traffic in each segment's corridor, during the five budgeting periods between 1970 and 1980, was developed by multiplying the 1985 estimate of divertible traffic by traffic increase factors determined for each freeway segment. A factor was defined to be the ratio of daily trip ends in a freeway segment's corridor during a budgeting period to the daily trip ends in the corridor in 1985. For example, the ratio of daily trip ends in a corridor during a budgeting period to the corridor's daily trip

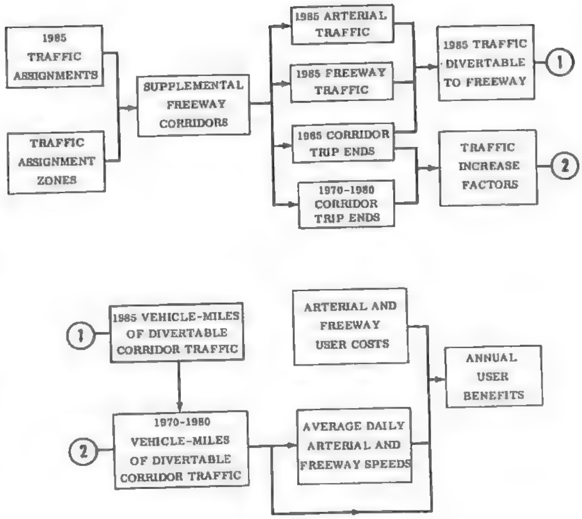

Figure 5. User benefit calculation.

ends in 1985 would be the corridor's traffic factor for the budgeting period. Multiplying this factor by the 1985 estimate of corridor traffic that is divertible to a freeway yields the divertible traffic for the budgeting period. Using this method, an estimate of average corridor traffic that is divertible to the freeway segment was prepared for each budgeting period.

With this traffic volume estimated, the travel speeds in the corridor were then prepared. Speeds on corridor arterials, assuming the freeway did not exist, were first determined. Next, these arterial speeds were estimated assuming that the freeway had been built. Finally, the speed on the corridor's freeway was estimated. Then the costs per vehicle-mile at these speeds, as developed by Haikalis and Joseph (5) but increased 20 percent to reflect the general price trend since the presentation of their paper, were used to calculate the differential cost to users who would be diverted to the freeway facility. This corridor differential cost or user return was determined for each budgeting period and multiplied by the previously determined corridor divertible traffic to obtain the total gross user benefit of the freeway segment in the corridor. Figure 5 is a detailed flow chart of the procedure for determining the total gross user benefit of each freeway segment.

This benefit value is not, however, equivalent to B_{ik}, the net benefit of a freeway segment defined in the objective function. As stated, the foregoing calculation defines the gross user benefits generated by a segment during a particular budgeting period. From this gross benefit, network cost must be subtracted to obtain a net benefit. These other costs include the segment construction and right-of-way costs allocated to a budgeting period and the costs of maintaining the freeway segment during the same budgeting period. More specifically, B_{ik} equals the user benefit (change in user costs) created by freeway segment i during budgeting period k, minus the portion of construction and right-of-way costs for segment i allocated to budgeting period k, minus the costs of maintaining segment i during budgeting period k.

If early acquisition of right-of-way is not considered, right-of-way for segment i must be purchased in the same budgeting period when construction of segment i takes place. Thus, the allocated cost per budgeting period in the objective function is the total cost (construction plus right-of-way) of the segment times the capital recovery factor. This allocation of right-of-way and construction costs to a budgeting period was accomplished with a capital recovery factor at 5 percent annual interest assuming a 50-year life for all freeway segments.

COST ALLOCATION, INFLATION, AND DISCOUNTING

It should be emphasized that there are differences between the definitions of construction and right-of-way costs in the objective function and the first constraint. These differences arise because of the handling of cost allocation, inflation, and discounting in these two parts of the formulation. As previously outlined, in the objective function only a portion of the total cost of the facility is allocated to each budgeting period over the life of the facility. This is accomplished with the capital recovery factor. However, in the first constraint the variable tc_{ij} is the total of construction and right-of-way costs associated with the facility if it is built in budgeting period j.

A second major difference occurs in the treatment of inflation in these costs over time. In the objective function, increases in the costs of construction and right-of-way due to inflation are ignored. It is assumed that the inflationary trend in both of these highway costs equals the inflationary trend in prices in general, including the user costs that are used to calculate the gross user benefit (6). The reformulation to include advance right-of-way acquisition does, however, permit increases in the cost of right-of-way above price increases attributable to inflation. In the first constraint, however, the situation is much different. Although construction and right-of-way costs may increase at a certain rate due to inflation, there is no guarantee that the available funds will increase at this rate. Unlike the case in the objective function, there is no reason to suppose that the inflationary trend in the highway costs equals the increase in the funds budgeted for construction and right-of-way expenditures on the supplemental freeway facilities. Thus, increases in construction and right-of-way costs due to inflation must be included in the analysis in the first constraint to ensure that inflated costs do not exceed the amount of available funds.

The final difference is in the relative importance of discounting in the objective function and first constraint. In the first constraint, all costs are measured at the same point in time; all money spent on construction and right-of-way for the freeway segments in budgeting period j must be less than or equal to the funds available in budgeting period j. Discounting costs and funds available do not affect this constraint because both sides of the equation are multiplied by the same discount factor, and thus discounting can be ignored. But in the objective function, benefits at different points in time are being totaled. In this case, discounting is important because a dollar of future benefit must be distinguished from a dollar of present benefit. In the objective function, the present worth, instead of the absolute dollar value, of all future benefits must be computed and used.

PERIOD OF TIME OVER WHICH BENEFITS ARE TOTALED

In the initial formulation of the problem, the summation of B_{ik} for all values of k is not limited by an upper bound on k, i.e., limited to any length of time. This unbounded upper limit serves only to represent the concept of a continuous return on a freeway segment through time. In practice, discounting future benefits generally allows a limit to be placed on the length of time over which the benefit of a freeway segment accumulates. Discounting reduces the significance of distant future benefits relative to near-term future benefits. The discounted return on a segment during a year far in the future will not add significantly to the total worth of the segment (7). This allows benefits from the future remaining lives of the segments to be ignored after a certain point in time.

This reasoning is the basis for developing an upper bound on the period of time over which a freeway segment's benefits are totaled. Note that the objective function can be broken into two separate expressions, one for all benefits occurring before the completion date of the network and a separate expression for all benefits accruing after completion of the network. Mathematically, this can be stated as follows:

$$\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=j+1}^{\infty} B_{ik}Y_{ij} = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=j+1}^{n} B_{ik}Y_{ij} + \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=n+1}^{\infty} B_{ik}Y_{ij}$$

The far right-hand side of this equation (the portion that accumulates benefits accruing after all freeway segments are completed) is nearly constant. Changes in the usable lives of the segments and related changes in their benefits, which are discounted from far in the future, do not greatly affect the total value of the objective function. Benefits from a segment between the completion of the network and before the segment's

usable life is exhausted are relatively independent of when the segment was constructed. The objective function can, therefore, usually be shortened to include only benefits before the network is constructed without changing the problem's solution. This equivalent objective function is

$$\text{maximize} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=j+1}^{n} B_{ik} Y_{ij}$$

EXTENSION TO EARLY RIGHT-OF-WAY ACQUISITION

In the initial formulation of the problem, early acquisition of right-of-way was not considered. To increase the realism of the analysis, it was decided that this potential course of action could not be ignored. Providing this option meant that the benefits associated with advance right-of-way acquisition had to be accounted for in the objective function. With respect to the costs included in the objective function, the effect of allowing early right-of-way acquisition is fairly obvious. Early acquisition may allow savings in the right-of-way costs allocated to a budgeting period and increase B_{ik}. However, these additional benefits accrue only if there is an increase over time in the cost of right-of-way above that explained by general price increases; otherwise, the initial formulation would still be appropriate.

In the initial formulation, the objective function was defined as follows:

$$\text{maximize} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=j+1}^{\infty} B_{ik} Y_{ij}$$

where B_{ik} is equal to the reduction in corridor user costs in budgeting period k created by construction of segment i in an earlier budgeting period minus the construction, right-of-way, and maintenance costs for segment i allocated to budgeting period k. Use of the same interest rate in the capital recovery factor and present worth calculations makes the present worth of the cost of right-of-way equal to the present worth of the series of allocated right-of-way costs in the objective function. Mathematically this may be stated as follows:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=j+1}^{\infty} B_{ik} Y_{ij} = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=j+1}^{\infty} B'_{ik} Y_{ij} - \sum_{i=1}^{m} \sum_{j=1}^{n} R_{ij} Y_{ij}$$

where

B'_{ik} = B_{ik} without the allocated right-of-way cost for segment i in budgeting period k included in the calculation, and

R_{ij} = the present worth of the right-of-way required for segment i if purchased in budgeting period j.

In this formulation, the right-of-way is still purchased at the same time that construction takes place.

In order for right-of-way to be purchased in a budgeting period other than when construction takes place, a new variable must be defined. This variable is X_{ij}, a variable analogous to Y_{ij} that applies only for the purchase of right-of-way. Placing this variable in the objective function changes the initial formulation to

$$\text{maximize} \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=j+1}^{\infty} B'_{ik} Y_{ij} - \sum_{i=1}^{m} \sum_{j=1}^{n} R_{ij} X_{ij}$$

where

X_{ij} = 0 if right-of-way for segment i is not purchased in budgeting period j,

X_{ij} = 1 if right-of-way for segment i is purchased in budgeting period j, and

R_{ij} = the present worth of the right-of-way required for segment i if purchased in budgeting period j (the cost of right-of-way in budgeting period j includes the uninflated increase in the cost of right-of-way).

In effect, this reformulation adds the objective of minimizing cost through early acquisition of right-of-way that will appreciate rapidly.

As before, the above objective function can be expanded as follows:

$$\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=j+1}^{\infty} B'_{ik}\,Y_{ij} - \sum_{i=1}^{m}\sum_{j=1}^{n} R_{ij}\,X_{ij} = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=j+1}^{n} B'_{ik}\,Y_{ij} - \sum_{i=1}^{m}\sum_{j=1}^{n} R_{ij}\,X_{ij} + \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=n+1}^{\infty} B'_{ik}\,Y_{ij}$$

The summation of benefits past the completion date of the network, the term to the far right of the equality, is nearly constant. As was explained earlier, this expression can be dropped from the objective function without affecting the problem's solution. Rewriting the above objective function without this term yields the bounded objective function for the mathematical program that includes early right-of-way acquisition:

$$\text{maximize} \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=j+1}^{n} B'_{ik}\,Y_{ij} - \sum_{i=1}^{m}\sum_{j=1}^{n} R_{ij}\,X_{ij}$$

REFORMULATION OF THE CONSTRAINTS

Attention will now be turned toward the constraints on the early right-of-way acquisition objective function. The constraint set prepared for the initial formulation is inadequate for this expanded problem. The first constraint must be revised so that the total cost of a segment, which includes right-of-way, is not always charged against the funds in the budgeting period in which the segment is built. Right-of-way and construction costs can now be charged to different budgeting periods. The second constraint of the original constraint set ensures that each segment is completed within n budgeting periods, and this constraint is still valid.

Constraints applicable to the advance right-of-way acquisition variables must be added to those constraints dealing with the original choice variables. A constraint that prevents right-of-way from being purchased more than once is needed. More importantly, a constraint to ensure that right-of-way acquisition takes place prior to construction of a segment is required. The formal representation of the reformulated constraint set is as follows:

1. $\sum_{i=1}^{m} cc_{ij}\,Y_{ij} + row_{ij}\,X_{ij} \le C_j$ if $1 \le j \le n$

2. $\sum_{j=1}^{n} Y_{ij} = 1$ if $1 \le i \le m$

3. $\sum_{j=1}^{n} X_{ij} = 1$ if $1 \le i \le m$

4. $\sum_{j=1}^{p} X_{ij} \ge Y_{ip}$ if $1 \le i \le m$, $1 \le p \le n$

5. $Y_{ij} = 0$ or 1

6. $X_{ij} = 0 \text{ or } 1$

where

cc_{ij} = the construction cost of segment i if built in budgeting period j, and

row_{ij} = the right-of-way cost of segment i if purchased in budgeting period j.

The reformulated problem, like its predecessor, is an integer linear programming problem, a problem that can be solved fairly simply because the integer solutions can be generated with exactly m of the Y_{ij} and m of the X_{ij} equal to one.

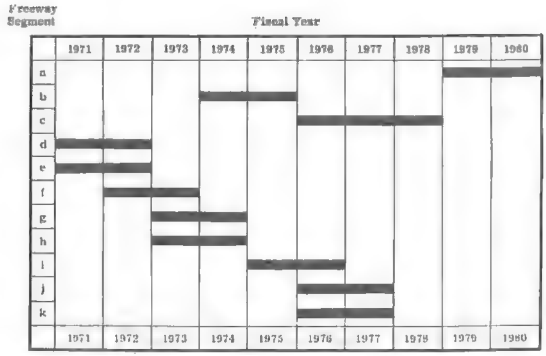

Figure 6. Example program developed from the analysis.

PRELIMINARY RESULTS

Approximately 30 runs of the initial mathematical programming formulation have been completed. The reasons for the large number of runs were to test the sensitivity of the solution to alternate budgets and to analyze the effect of allowing the transfer of funds between budgeting periods. Even with this number of runs, the total cost of computer time for the linear programming routine used in the analysis was less than \$100. The reformulated mathematical program that includes advance right-of-way acquisition has also been run successfully several times. Although this reformulation created a substantially larger problem, computer costs still remain reasonable; each run of the reformulated problem cost approximately \$10.

The results obtained from the initial formulation permitted the establishment of preliminary project priorities and a construction program for completing the 11 segments included in the analysis. An example of the type of program that can be easily developed from this analysis is shown in Figure 6. Budgeting period expenditures for right-of-way and construction are ordered by segment and do not exceed the funds available in each budgeting period. In addition to this information, the results of the reformulation show, by freeway segment, where advance right-of-way acquisition is beneficial.

CONCLUSIONS

Perhaps the most important aspect of the use of mathematical programming in this study is that such methods permit sensitivity analyses to be performed quite easily. Effects of alternate budget allocations and segment costs on the problem's solution are readily obtainable. Such information provides a base for cost-effectiveness analysis and similar evaluation procedures, which then feed back information to the budget allocation process.

Even though the present problem considers only a limited number of network segments, the expansion of the mathematical programs in the analysis to large networks is quite practical with the development of extremely efficient and large-scale computer codes for solving mathematical programming problems. Eventually, a similar analysis is planned for the entire network included in the CATS area, the complete Chicago metropolitan area. This intermediate-level planning will provide a link between the long-range transportation study at the regional level and the selection of specific projects to develop the plan on the ground.

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Problems, Misconceptions, and Errors in Benefit-Cost Analyses of Transit Systems

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This paper is addressed to the process of evaluating transit systems alternatives in metropolitan areas. The conclusions are derived from the author's experience in conducting such studies and from a review of a number of recent reports. Some 15 separate issues are discussed, and conclusions are drawn as to appropriate research methods for each subject. First, the alternative of not conducting a benefit-cost analysis is discussed, and reasons are described why other methods,(e.g., professional judgment, cost of service, and financial feasibility) may lead to incorrect decisions. Conclusions are then drawn concerning the use of rating systems versus dollar-based evaluations, discounting, the choice of an interest rate, financing considerations, inflation, reflection of all public costs, the use of benefit-cost analysis only as justification for a single recommended system, the structuring of alternatives, analyzing benefits only to existing travelers, modal split and traveler benefit inconsistencies, measurement of motor vehicle running costs, factoring from daily savings to yearly savings, economic valuation of noneconomic factors, treatment of uncertainty, and interpretation of benefit-cost ratios.

•OFFICIALS in an increasing number of cities have recognized in recent years that continued construction of freeways in heavily populated areas does not provide the kinds of transportation improvements needed. They are now considering investments in new mass transit systems to assist in solving their congestion problems. Transit investments also offer improvements in transportation to those persons who cannot drive, do not own or have access to an automobile, or simply do not choose to drive. Studies of transit system alternatives in these cities include a number of tasks—transportation planning, system engineering, construction engineering, architecture, financial planning, and others.

Benefit-cost analysis is becoming increasingly recognized as an additional task that should be included in studying transit systems. It can provide local officials and the public with improved knowledge both about the desirability of alternative systems and about the equity of potential financing schemes. Benefit-cost studies are appearing more frequently in the technical literature and as chapters to consultants' reports on the feasibility of specific urban transit systems.

The use of benefit-cost analysis in highway planning first appeared in the literature of the 1920s. Since then, various procedures and practices have been soundly attacked and continually improved. Some years ago, Grant and Oglesby (1) did a great service to the development of objective decision-making in highway planning by reviewing and criticizing certain studies of the economic feasibility of highway investment projects. In this review, they pointed out errors that had been observed in the definition of alternatives, in selection of an interest rate and a study period, and in the need for considering nonuser consequences.

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The present paper discusses similar considerations for transit systems. The procedures and practices used for evaluating them are also subject to criticism and improvement. In the next section, various methods—other than benefit-cost analysis—for reaching decisions on transit systems are described and criticized. Subsequent sections discuss the following specific issues in designing and executing benefit-cost analyses: rating systems versus dollar-based evaluations, discounting, choice of interest rate, financing considerations, inflation, reflection of all public costs, benefit-cost analysis as justification for a single recommended system, structuring of alternatives, analyzing benefits only to existing travelers, modal split and traveler benefit inconsistencies, measurement of motor vehicle running costs, factoring from daily savings to yearly savings, economic valuation of noneconomic factors, treatment of uncertainty, and interpretation of benefit-cost ratios.

In this paper, the term "benefit-cost analyses" is used in a general sense. Socioeconomic evaluation or cost-effectiveness analysis are alternatives that might have been chosen. The term implies an evaluation that reflects impacts of alternative transit systems on the public and that attempts to reduce the impacts to dollar values wherever possible and appropriate.

The discussion derives from the experience of the author and his colleagues in conducting transit system evaluations and from a review of a number of recent studies conducted in various cities. All of the problems and errors are taken from published reports. Some even are serious enough to have led to an incorrect conclusion as to whether benefits exceed the costs.

ALTERNATIVE OF NOT CONDUCTING A BENEFIT-COST ANALYSIS

Before discussing some of the problems in conducting benefit-cost analyses, it is appropriate to consider the alternative of not conducting a benefit-cost analysis at all. In the past, studies of mass transit that have not used benefit-cost analysis have resorted to a variety of means to justify their recommendations. Among them are professional judgment, cost of service, and financial feasibility.

In the professional judgment approach, the consultant generally cites a range of facts and factors that he feels are important and then states a judgment or a recommendation without stating any objective basis. When an alternative that is not recommended has some features that are more attractive than those of the recommended alternative, the trade-offs are usually not explicitly defined. Opinions as to the desirability of certain features of rejected alternatives are frequently stated in a manner that discourages debate.

The cost-of-service approach is more quantitative in nature than the professional judgment approach. Cost data are developed that can be reduced to an index number, such as the cost per seat-mile or cost per passenger-mile. Such indexes are valuable in understanding the cost-productivity relationships between alternative systems, but they do not reflect all factors that should be considered in choosing a system.

Consider, for example, a hypothetical set of alternatives having different degrees of coverage of the urban area. One might provide high-quality service to the downtown and inner city portions of the area; the second might provide lower quality service to the downtown portion but also provide service to the medium-density areas; and the third might provide extended service all the way from downtown into the low-density suburbs. It would not be surprising to find that the first and third alternatives had higher average costs per passenger-mile than the second—the first because of high capital costs per mile for right-of-way and construction, and the third because of low patronage from the low-density areas. Thus, on the basis of this indicator, the second alternative might be recommended. However, it is obvious that the second alternative may not be the most desirable. The first might be considered most appealing because of its potential for reducing congestion and air pollution in the most densely populated areas of the city; the third might be considered most appealing because of the backhaul service provided to residents of the inner city o. because of its greater effect in maintaining a successful central downtown.

The third approach, financial feasibility, focuses on the impact of a new system on the transit operator rather than on the public. It compares the estimated revenues of

the proposed system with the estimated costs. Three methods of analyzing financial feasibility can be found in the literature. They are the total cost method, the capital cost method, and the yearly revenue-cost method. The total cost method entails a comparison of total revenues with total costs in a manner not unlike that often used to evaluate the economic feasibility of a business enterprise. In some cases, the method used is simple arithmetic summation of all costs and revenues over the expected life of the system; in others, discounting techniques are used. With this method, the alternative with the greatest excess of total revenues over total costs is favored. In the capital cost method, alternatives are compared in terms of the total capital expenditures and may be rejected if it appears that expenditures cannot be financed through taxation. The third method, comparison of yearly operating revenues with operating costs, has recently been used in a number of cities. Here it is presumed that the capital costs of the system are to be paid by the general public through some form of taxation. Thus, a system is feasible if operating revenues exceed operating costs, and sometimes a system is recommended simply if its excess of operating revenues over operating costs is greater than that of the other alternatives.

The fundamental criticism of the financial feasibility approach is that it takes the wrong point of view. What is important is not how well the operator succeeds (although, obviously, investment by a private operator has to attract at least a minimum attractive return) but how beneficial the proposed system is to the public. Such an approach also masks the problem of establishing an optimal fare structure from the public's point of view. The financial analysis is a necessary part of an overall study because the operator must be financially solvent. The essential point is that it should not be used as the sole criterion on which the most desirable system is chosen.

RATING SYSTEMS VERSUS DOLLAR-BASED EVALUATIONS

In a number of studies of urban transportation, rating systems have been used to compare alternatives. Usually, the construction of a rating system of evaluation entails (a) identification of the factors to be rated, (b) estimation of a numerical value of each factor for each alternative transportation system, (c) generation of a rating or weighting for each numerical unit of the factor, and (d) development of an overall index or rating for each alternative. Errors in evaluation are most frequently generated in the last two steps.

One example of misuse of the rating system occurred in a rapid transit study of bus and rail alternatives for a metropolitan area. In this study, ten alternatives were evaluated on each of six factors. For each factor, the ten alternatives were assigned rankings from one to ten. Then the numerical values of the rankings were added up, giving a ranking summary from which the recommended alternative was chosen. Table 1 gives the results of the ranking, along with cost and patronage data for the ten alternatives.

TABLE 1

EVALUATION SUMMARY OF MAJOR TRANSIT SYSTEM ALTERNATIVES

Alternative	Evaluation Item: Cost Per Passenger Trip		Capital Cost for System		Passengers Attracted, Automobile Travel Reduction		Operational and Physical Feasibility, Rank	Staging Possibilities, Rank	Community and Regional Objectives, Rank	Ranking Summary	Recommended Alternative
	Rank[a]	Cost in Cents	Rank	Cost[b]	Rank	Thousands of Daily Passengers					
A	10	28	10	460	8	330	3	10	8	49	—
B	9	24	6	385	7	335	5	8	5	40	—
C	7	23	8	400	2	350	1	7	3	28	Acceptable
D	5	22	5	375	4	345	2	4	4	24	Best
E	6	23	7	390	3	345	8	3	2	29	—
F	8	24	9	420	1	355	6	9	1	34	Acceptable
G	1	11	1	140	10	285	10	5	10	37	—
H	2	17	2	260	7	305	7	1	9	30	—
I	3	21	3	350	4	340	4	6	7	29	Acceptable
J	4	21	4	360	9	345	9	2	6	30	—

[a]1 = best ranking; 10 = worst ranking.

[b]Cost in millions of dollars, 1966-1967.

This case presents a particularly misleading use of rating systems. Equal rankings on two factors are given equivalent weights in the summary evaluation, yet one factor may be far more important than another. For example, the community might place much greater weight on the attainment of community and regional objectives than on staging possibilities. A weighting scheme that would relate the importance of each criterion to the others would mitigate this error. However, data to permit reliable weighting and combination of diverse criteria are difficult to obtain and, in their absence, the ratings should not be combined in any way (2).

An additional problem is created if whole numbers (1, 2, 3, . . .) are used in the ranking system. Alternatives that differ very little on an absolute basis must differ by at least one rank unit in the ranking system. In Table 1, note that alternatives B through F differ in cost per passenger trip by less than 10 percent, yet the range of rank values is from 5 to 9. This range of four units must be greater than the true differences in value. The same problem appears in the ranking of the capital cost and the passengers-attracted criteria.

Still another problem that can be noted in the example is the way in which factors are implicitly treated as being independent in the assignment of ranks and in the addition of rank values, in spite of the fact that considerable dependence between them exists. The cost per passenger trip is a function of the capital cost and of the number of passengers attracted, among the factors listed. A low ranking on one will lower the ranking on the other.

DISCOUNTING

Discounting techniques are widely applied to reflect the time value of money in studies of the feasibility of public and private investments. These techniques permit the decision-maker to realistically reflect the fact that, because of the time value of money, future dollar expenditures have less utility than present expenditures. This difference in value is accounted for by the fact that the dollars received earlier can be invested and can earn interest before the distant future dollars are received. Even if not invested, the present dollars can be used for purchasing goods or services, and the benefits from these goods and services can be enjoyed sooner.

To adjust the benefits and costs for time differences, it is necessary to discount them—to multiply them by a factor that depends both on the time of their occurrence and on the rate of interest. The rate at which the costs and benefits in the study should be discounted depends on the value of money over time to those who must bear the costs. For public investments, rates of 5 to 10 percent are commonly used. By applying formulas based on the interest rate, the benefits and costs occurring in future years can be converted to their worth at the present time. Using other formulas based on the interest rate and study period, the value at the present time can be converted further to an equivalent uniform annual cost. The equivalent annual cost may be thought of as the annual amount that would have to be spent to repay a loan with interest.

Although many concepts in the fields of economics and engineering economics are subject to variations in opinion, the concept of discounting is universally accepted. Yet, one recent study was presented to the voters of a metropolitan area with undiscounted money data. Figure 1 shows the conclusion of the economic and social benefits section of the report in terms of the cumulative flow of costs and benefits. The text states, "By 1979, the cumulative flow of benefits would begin to exceed the cumulative cost flow . . . . The conclusion to be drawn from this analysis is that anticipated quantifiable benefits from transit exceed anticipated costs." One is led to wonder if, using discounting techniques, the net present worth of the benefits exceeds the net present worth of the costs.

CHOICE OF INTEREST RATE

As indicated earlier, most experts recommend the use of an interest rate between 5 and 10 percent for public investments. In addition to the error of not using discounting techniques at all, which is equivalent to using a 0 percent interest rate, is the error

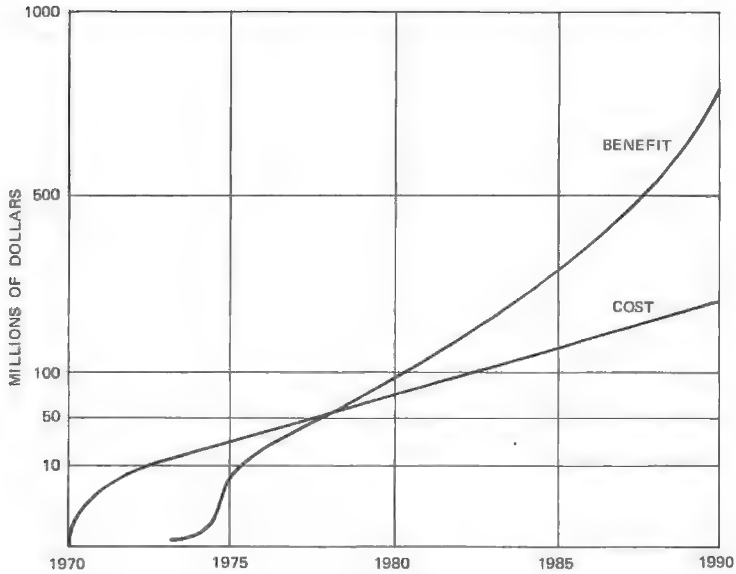

Figure 1. Cumulative cost/benefit flow.

of using an incorrect rationale for determining an interest rate and the resulting application of an inappropriate interest rate.

A number of bases have been offered in the literature for the choice of an interest rate for government investments, including the social discount rate, the opportunity cost of capital, the government bond interest rate, and the marginal rate of return. Opportunity cost appears to have the widest professional acceptance at present (3, 4). Inasmuch as the fundamental source of funds for government investments is the general public, the opportunity cost rationale asserts that an interest rate be chosen that represents the opportunity cost of money taken in the form of taxes from the hands of the general public. Opportunity cost is therefore based on foregone opportunities for private investment.

The most popular mistake in choosing an interest rate made in some recent transit studies is to base the rate on the cost of public borrowing. The argument in one report was stated as follows:

> Although trends in the last few years have indicated a 5 to 5.5 percent average present worth discount factor, this is assumed to be a short term phenomenon, and 4 percent, as used by most public agencies, is considered more appropriate to represent typical interest rates in public borrowing. In this analysis, therefore, the total revenues occurring during the 50-year life span of the project have been discounted at 4 percent compounded annually.

(Even though this quote uses the term "revenues", elsewhere in the report it is disclosed that the 4 percent figure was applied to benefits.)

Another transit benefit-cost study exhibits the same thinking:

> Local Member Grants, comprising the balance of net project costs, were annualized over a period of 37 years–equivalent to 4%, 25-year bonds issued during the construction period . . . both benefits and costs were multiplied by a discount factor equivalent to 4% compounded to reconcile the effects of timing on annual flows.

In most transit studies, a number of different interest rates may be found. It is imperative that they not be confused. In these two examples, it is clear that the difference between public borrowing interest rates and the opportunity cost interest rate has been

confused. The fact that a public agency may be able to borrow money at an interest rate of, say, 4 percent has no bearing on the choice of an interest rate for discounting purposes. The borrowing rate is used to compute the costs entailed in repaying a loan for capital expenditures, and must therefore indicate the magnitudes of money that must be collected year-by-year by the transit operator to repay the borrowed funds. In contrast, the opportunity cost interest rate is used to compute the present value or the equivalent annual value of a series of benefit and cost flows. This computation is used to indicate the differences between benefits and costs that are incurred at different times.

Although a difference of 1 or 2 percent in the interest rate may sound minor, results of an economy study can be sensitive to such variations. For example, using a rate of 4 percent instead of 6 percent for discounting uniform annual benefits over a 30-year study period will cause an increase of approximately ¼ in the present value of the benefits.

FINANCING CONSIDERATIONS

Recent studies of benefits and costs of public transportation systems have differed on the question of whether to include the effects of financing in the analysis. In these cases, the question of financing arose as a consideration in project planning because the construction cost of the project was to have been financed through bond issues and repaid by the general public through increases in sales or property taxes.

One argument for not including financial considerations in a benefit-cost study is the well-accepted principle that separate decisions should be studied separately. Following this rule, the cost and effectiveness of alternative systems should be assessed first, and then the project that is most desirable should be studied from the standpoint of the most feasible financing alternatives.

The fact of the matter is, however, that the financing decision in most cities is not entirely separable from the system decision. Even though the city's engineering and financial consultants and elected officials may have considered these issues separately, the final decision is left to the public. The voting public is offered a package and is asked to accept or reject that package, which includes both the proposed system and the proposed method of financing. In such cases the decisions are not, in the final analysis, separable.

There is another argument to support the inclusion of financing considerations in the benefit-cost study. It is increasingly recognized that a simple sum of benefits and costs over the entire community does not fully illuminate all facets of the decision. Elected officials and the public are concerned also with the manner in which the benefits and costs would be distributed among the various groups in the community. A public transit project will affect travelers, businessmen, property owners, unemployed persons, and taxpayers differently. The benefit-cost study should display these differential effects. Thus, the amounts and timing of repayments of the borrowed capital should be displayed in the context of the persons who will be burdened by the repayment requirements. The recommended scheme should be developed to display the impacts of all of the benefits and costs on each of a number of groups in the community.

This author, therefore, would advocate estimating benefits in reference to the service life or study period of the project, and comparing these benefits with the debt repayment costs over the same period. Such a procedure permits the study to display the distributional effects. In it, the capital costs would be converted to the bond repayment amounts over the life of the bond issues. These amounts would include both repayment of the principal and the associated interest costs, and would be computed at the bond interest rate. This flow of costs should be compared with the flow of benefits over the study period, and a subtraction of one from the other would indicate the net value of those criteria considered costable. These values can then be considered in reference to the criteria that are not costable.

If the benefits and costs, including financing costs, are considered to be constant over the study period, the net difference between annual costable benefits and annual loan repayment costs can be directly evaluated. The difference will be a single figure. However, a more accurate representation of the situation may recognize that growth in

population and increases in travel will change the amounts of the benefits over time. For example, benefits might increase over a portion of the study period up to a point at which the system's capacity is reached. When flows of benefits (or costs) are predicted to change over time, the problem of assessment is complicated; it is not possible to judge the costable aspects of the system from a single year's data. Here, as indicated earlier, benefits and costs should be discounted, and a single present value of the net benefits or equivalent annual net benefit should be computed. Such a procedure will produce a single index of the costable criteria that will be useful for decision-making.

The procedure may appear to be an exercise in sleight-of-hand, however, when the interest rate on bond repayment is different from the interest rate based on opportunity cost used in the discounting process. If, as is usually the case, the interest rate for bond repayment is lower than the rate used for discounting, the project cost will appear cheaper, in terms of the present worth of repayment amounts, than the actual capital cost. For example, assume a 4 percent interest rate on bond repayment, a 6 percent opportunity cost discount rate, and a 40-year study period and bond repayment period. A project whose capital cost is $1 billion will then have an annual loan repayment cost of $50.5 million, but the present value of those loan repayments is only $760 million, or 24 percent less than the actual capital cost.

The $240 million difference between the actual present cost and the present value of the loan repayments appears to be a benefit that has materialized out of nowhere. Yet, such is the case for all local projects that are financed by municipal bonds, because of income tax regulations. The current IRS procedures leave interest income on municipal bonds tax-free. This procedure has permitted local governments to finance capital improvements at low interest rates and taxpayers to gain tax-free income. The local government and its citizenry gains, and the bond buyer gains. The "loser" is the federal government.

INFLATION

Most studies of transit systems recognize that inflation may have a significant effect on transit projects. Estimates are made in most studies of the effect of inflation on construction costs, to ensure that the amount of money obtained will be sufficient to pay for costs as they are incurred in the construction period. However, other costs are also affected by inflation.

Recent benefit-cost studies have taken different positions regarding how the overall effects of inflation should be reflected in the analysis. One study incorporates actual inflationary trends: "Dollars have been inflated on the basis of 4.5 percent annually for construction-related items, 6.0 percent annually for wage-related items, and 2.5 percent annually for money-related items."

In another study, construction costs were inflated at an expected value of increase of 7 percent, and benefits were inflated at 2 percent per year. This study reflected the fact that the project costs incurred by the community would be fixed bond repayments, not capital costs, and that these costs would be paid in inflated dollars. It also reflected the fact that benefits would also be received in inflated dollars:

> . . . The value of the benefits to be received has been estimated in terms of present-day dollars. The amount required to pay the interest and principal due each year on bonds is fixed by the bond terms, but may decline in value by today's standards because of decreased purchasing power of the dollars used to make these payments. We have therefore increased the benefits at a constant annual rate to measure the value of the benefits and the amount of money paid for bond service in any year in equivalent dollars.
>
> There has been a general trend toward lower purchasing power of the dollar. The cost of living, measured by the consumer price index produced by the U.S. Bureau of Labor Statistics, has increased in every year but one since 1949. The rate of price increases varies widely from product to product and from year to year due to public policy, reflected by governmental spending, and as a result of the dynamics of the economy. It is generally agreed that the overall value of the dollar is decreasing at a rate between 1.5 and 2.0 percent per year for the United States, and estimates for (the study area) tend toward the higher figure. We have therefore used 2 percent as the rate of increase in the value of increase in benefits.

A third study concludes that it is inappropriate to include inflationary effects:

> All benefit and cost flows examined in this report are measured in 1968 constant dollars. The effects of inflation have been factored out in both flows for several reasons. First, inflating dollar benefits or costs does not actually represent a "net" increase in their real value—it simply reflects an absolute increase in monetary value. In addition, the effects of inflation over so large a time segment containing numerous benefit and cost components are extremely volatile and difficult to estimate. Finally, we do not believe that benefits and costs, flowing over different time segments, can be validly compared if they are inflated. For these reasons, we have inflated neither benefits or costs.

The problem of deciding how to handle the question of inflation in a benefit-cost study is one of the more difficult problems that must be resolved. One of the best studies made is by Lee and Grant (5). In their work, the authors make two important distinctions (a) between general inflation and differential price changes and (b) between the local viewpoint and the national viewpoint. Both distinctions are crucial to deciding how to handle the question of inflation.

They conclude, as do others in the literature they review, that general inflation effects should not be included in transit studies but that "in principle, expected differential price changes should be included in an economy study." However, they recommend that, for highway economy studies, ". . . there are good reasons for using current prices to evaluate costs and benefits."

Their conclusions regarding the local versus the national viewpoint are made with respect to general inflation. They state that, in the local case, ". . . the repayment of the debt can be made with inflated dollars which means that the real cost to the area is less than it would have been had inflation not occurred. A loss occurs to the creditors who failed to anticipate inflation, but this is generally of little concern to the local area." But in the national case, because losses to creditors and gains to debtors are both of concern, they recommend that general inflationary trends not be considered in the economy study.

In this author's view, the evaluation of transit systems is different from the evaluation of highway projects in a number of important ways. First, transit systems are frequently financed in part by the sale of bonds, whereas highways are built with current tax revenues. Second, the decision on whether to go ahead is usually made with a financing plan as an integral consideration of the total decision, and it is a local decision. Third, there is need to study a range of system alternatives that may be affected differently by price changes, e.g., a capital-intensive system versus a labor-intensive system. Fourth, the magnitude of the project frequently is such that several years may pass between the time that the decision is made and the system is finally operating (San Francisco's BART system will require 9 to 10 years). Changes in prices over this period must explicitly be considered in planning the project.

These factors argue for including differential price trends in the benefit-cost analysis: benefits are affected by inflation, whereas debt repayment is not—once the repayment schedule is fixed. If the community gains by the fact that creditors have not anticipated inflation, the gain is real. Systems that are more capital-intensive stand to gain because of inflation relative to those that have a high labor content. Finally, it is difficult to obtain additional funds if inflation has not been properly allowed for.

The decisions on the choice of differential price change factors, on the potentially feasible financing interest rate, and on the interest rate to be used for discounting should be made in careful relation to one another. Consideration should be given to the degree to which the effect of inflation should be reflected as a separate factor, or included in the interest rate used for discounting (6).

REFLECTION OF ALL PUBLIC COSTS

In many rapid transit projects, the process of raising and managing funds for construction and operation requires careful study. Frequently, the responsible agency will engage a financial consultant to develop plans for the financing aspects of the project development. The consultant will be concerned with the type of bonds to be floated, their amounts and timing, the tax funds to be collected, and their amounts and timing.

These data, together with the capital and operating cost payment schedules and the revenue schedules from transit operations, are assembled into a total financial estimate of the agency's operations. The problem is made more complex when the new project's financing is to be combined with the financial results of an existing transit operation.

Failure to understand the financial planning can lead to errors in a benefit-cost analysis. In one recent study, the benefit-cost analyst took as the project costs the flow of money required to pay off the bonded indebtedness and failed to appreciate the fact that, during the early years of the project, more money would be collected in taxes than would be required to service the bonds. The financial consultant planned to use the surplus to pay directly some of the construction costs and thereby reduce the required borrowing.

This example points out two guidelines: first, that the benefit-cost analyst must clearly understand all aspects of the financial plan if he is to incorporate the distributional effects of financing in his study and, second, that the use of separate contractors for financial analysis and benefit-cost analysis may result in communications failures.

In another recent study, the total benefits from rapid transit were compared with only the local share of the anticipated capital costs, because two-thirds federal funding was anticipated. The transit system was estimated to produce benefits that would exceed the local costs, and thereby produce a local net benefit. On this basis the consultant recommended that the public approve the impending bond issue. But if the federal share had been included, it would have been clear that costs exceeded benefits.

BENEFIT-COST ANALYSIS AS JUSTIFICATION FOR A SINGLE RECOMMENDED SYSTEM

The magnitude of proposed transit investments outclasses most urban area capital projects. Recently in Los Angeles, a rapid transit system having an estimated capital cost of about $2.5 billion was proposed to the voters. This is one of the largest single capital investments ever considered by an urban area, and transit proposals in many other cities are proportionately as costly for the population of the area served.

The sheer size of such projects calls for careful appraisal of alternatives, because errors in decisions can have large effects in terms of unrealized or overstated benefits. All too often, benefit-cost analysis is called for only after the final design and route configuration have been chosen. The public is presented with a "to build or not to build" choice. It is thus not surprising that considerable opposition is raised by those who believe that the chosen system is not the most desirable. Instances can be cited in which proponents of other kinds of systems or of other route configurations have caused considerable unrest in the community by independently offering their concept of what is best. Even if the decisions that have been made by the transit agency and its consultants have been correct, calling in the benefit-cost analyst only to appraise the go, no-go decision carries the risk of losing public support.

More important, however, is the possibility that the final system is not the best choice. There is no assurance that decisions among alternative systems based on technical considerations or certain analytical practices described earlier will be the same that would have been reached by a well-structured benefit-cost analysis.

The obvious procedure is to conduct analyses of the benefits and costs of all meaningful alternatives and to present the results of those analyses to the public through its representatives. Also, the phrase "all meaningful alternatives" should be broadly construed, both because expansion of existing systems may be feasible in some urban areas and because radically new transit systems may be only a few years away. The following points are made to illustrate these possibilities in more detail:

1. One important source of opposition to transit programs is the sector of the public who are proponents of automobile travel and highway construction. These groups argue for the unquestioned benefits of flexibility and independence of travel of private transportation, but usually without quantitative data. The responsible transit agency should recognize this point of view, even the possibility that it may be correct. One way of considering this possibility is to structure a highway program of the same capital cost magnitude and to analyze the benefits and costs, including undesirable side effects, of

such a program within a framework consistent with that used to analyze transit alternatives.

2. Recent studies sponsored by the federal government indicate that entirely new systems of public transportation may provide considerably improved service at reasonable costs. Such systems are not available at present but could be developed for future implementation if a vigorous program of research and development were undertaken. Local transit studies should therefore explicitly compare the benefits and costs of waiting for a new system with those of immediately constructing a currently available system.

Beyond the issue of considering all valid transportation alternatives, more questions should probably be raised in rapid transit studies regarding complementary investments in city and environmental planning along transit rights-of-way, alternative ways of achieving certain subobjectives of public transportation (such as improved service between low-income neighborhoods and potential employment locations), and trade-offs between transportation investments and other means of achieving basic city goals. To cite only one example of such a trade-off, it is usually the aim of cities to reduce or reverse the emigration of middle- and high-income families to the suburbs, yet rapid transit may accelerate the exodus by making it easier and cheaper to commute long distances. Detailed comments on alternative mixes of public expenditures to better achieve such broad community aims and values are beyond the scope of this paper, but it should be clear from this single example that the interdependencies and feedback effects in cities, as in any complex system, must be recognized.

STRUCTURING OF ALTERNATIVES

Developing the appropriate structure of alternatives is a fundamental requirement in all benefit-cost studies, and errors in this step can result in errors in the benefits reported. One recent study of rapid transit in a large metropolitan area made a gross error of this type. In this report the valid point was made that the community could build a rapid transit system or more freeways and surface streets. However, benefits were estimated in relation to the existing freeway and street system, and these benefits were erroneously added to "cost saving" items, including additional miles of freeways and surface streets not required.

A correct structuring of alternatives would have recognized three separate alternatives:

1. Do nothing (d.n. in the following discussion);
2. Build a rapid transit system (r.t.); or
3. Build more freeways and streets (f.s.).

With such a structure, the benefits of rapid transit should be measured in relation to the do-nothing alternative. The travel benefits are the difference in travel costs between the two alternatives:

$$\text{Travel Benefit}_{\text{r.t.}} = \text{Travel Cost}_{\text{d.n.}} - \text{Travel Cost}_{\text{r.t.}}$$

The travel benefit should be compared with the cost of building the rapid transit system in order to assess feasibility. The net travel benefit is

$$\text{Net Benefit}_{\text{r.t.}} = \text{Travel Benefit}_{\text{r.t.}} - \text{System Cost}_{\text{r.t.}}$$

Similarly, the benefits of more freeways and streets should be measured in relation to the do-nothing alternative. The travel benefits are the differences in travel costs between the two alternatives:

$$\text{Travel Benefit}_{\text{f.s.}} = \text{Travel Cost}_{\text{d.n.}} - \text{Travel Cost}_{\text{f.s.}}$$

This travel benefit should be compared with the cost of building the freeway and street system improvements in order to assess feasibility. The net benefit then is

$$\text{Net Benefit}_{\text{f.s.}} = \text{Travel Benefit}_{\text{f.s.}} - \text{Investment Cost}_{\text{f.s.}}$$

Finally, the feasibility of the rapid transit alternative as compared with the freeway and surface street alternative is

$$\begin{aligned}\text{Overall Benefit}_{\text{r.t.}} &= \text{Net Benefit}_{\text{r.t.}} - \text{Net Benefit}_{\text{f.s.}}\\ &= \text{Travel Benefit}_{\text{r.t.}} - \text{System Cost}_{\text{r.t.}}\\ &\quad - \text{Travel Benefit}_{\text{f.s.}} + \text{Investment Cost}_{\text{f.s.}}\end{aligned}$$

If the overall benefit is positive, the rapid transit system is preferred to the alternative of freeway and street improvement. Yet, in the study report referred to above, benefits were computed as

$$\begin{aligned}\text{Overall Benefit}_{\text{r.t.}} &= \text{Travel Benefit}_{\text{r.t.}} - \text{System Cost}_{\text{r.t.}}\\ &\quad + \text{Investment Cost}_{\text{f.s.}}\end{aligned}$$

This same study made a similar error of including operations and maintenance costs of the freeway and street system as a savings resulting from rapid transit. The total amount of items erroneously included reaches $749 million. The overall net benefit claimed was $822 million; it should have been $73 million.

ANALYZING BENEFITS ONLY TO EXISTING TRAVELERS

For a number of reasons, transit authorities have sometimes restricted a benefit analysis to only the traveler (or user) benefits and thereby have not recognized or pursued studies of other benefits that may accrue to the area. Some of the technical literature has supported this view on the grounds that all effects beyond the direct effects on travelers are simply transfers of benefits from one sector of the community to another. This argument asserts that adding more general community benefits to traveler benefits results in a fundamental error of double counting.

However, even though errors of double counting should be meticulously avoided in all phases of a benefit-cost analysis, such a procedure should not be applied so as to eliminate consideration of community effects. Even if traveler benefits are transferred to other members of the community, analysis of such transfers can be included by tracing the transfers as far as possible but not adding them to total benefits. Other community effects may be identified that are not transfers and should definitely be included in the study.

Imperfections in the current state of the art of benefit-cost analysis in transit studies result in increased possibilities that benefits to other than present travelers may not be recognized. For example, most studies measure travel demand in terms of a trip table—a table showing the number of trips between each pair of travel zones—that is held fixed for all alternatives to be analyzed. Under these conditions, the analysis does not recognize that a new system may cause some travelers to choose different origins or destinations and may result in some persons taking trips that they would otherwise not have taken. Persons who make different trips or who travel more must certainly benefit from such actions or they would not choose to do so. Yet a traveler benefit analysis conducted under the assumption of a fixed trip table would not identify those benefits.

Even with more advanced analysis techniques, such a procedure of redistributing trips for each system alternative (with a trip distribution model) or using a travel demand model that reflects the characteristics of the transportation system and thereby estimates varying amounts of demand under conditions of varying accessibility may not identify and measure such benefits. The advanced technique may not, for example, adequately reflect the fact that increased accessibility may reduce unemployment and thereby produce a sizable community benefit.

A view that the benefits of transportation systems are not adequately measured solely by the reduction in transportation costs should be fundamental to the study. Travel usually takes place not for travel itself, but to obtain some beneficial effect at another location. Thus, the net value of a trip is equal to the following difference:

$$\begin{bmatrix}\text{Value of being at} \\ \text{place "X" (place value)}\end{bmatrix} - \begin{bmatrix}\text{Cost of getting to "X"} \\ \text{(transportation cost)}\end{bmatrix}$$

This view may someday be made operational through a computational procedure, but until further research makes that possible, it will help at least to identify any benefits that are not measured in the analysis. Furthermore, it will help to trace the benefits of travel to their ultimate recipients, who may not always be the travelers.

It is recommended that transit benefit-cost studies (as well as highway benefit-cost studies) consider a range of possible effects, such as the following:

1. Transit user effects;
2. Highway user effects, including savings in (a) travel time, (b) operating costs, (c) ownership costs, (d) accident costs, and (e) parking costs;
3. Unemployment effects;
4. Educational opportunity effects;
5. Business productivity effects;
6. Government productivity effects;
7. Real estate effects;
8. Life-style effects;
9. Environmental pollution effects;
10. Tax effects;
11. Disruption effects, including those that are (a) temporary during construction and (b) permanent in neighborhood division;
12. Construction labor effects;
13. Highway construction effects;
14. Aesthetic effects;
15. Property losses and relocation effects;
16. Regional and neighborhood growth effects;
17. Crime effects;
18. Civil defense effects;
19. Achievement of desired urban form;
20. Detailed nodal studies and projections;
21. Implementation evaluation;
22. Financing effects; and
23. Tourism effects.

MODAL SPLIT AND TRAVELER BENEFIT INCONSISTENCIES

In certain instances, the procedures used to estimate patronage of transit systems and those used to estimate traveler benefits lead to inconsistent results. Such an instance is shown in Figure 2, where an existing highway would compete with a proposed transit system for trips between zones A and B. From zone centroid to zone centroid, the travel times by highway and transit are 30 and 36 minutes respectively.

Without transit, all travelers would use the highway route, and each would travel 30 minutes from A to B. With transit, using a typical modal split procedure, a diversion from highway to transit would be computed in relation to travel times. Such a model might forecast the transit percentage of the total on the order of 20 percent. With

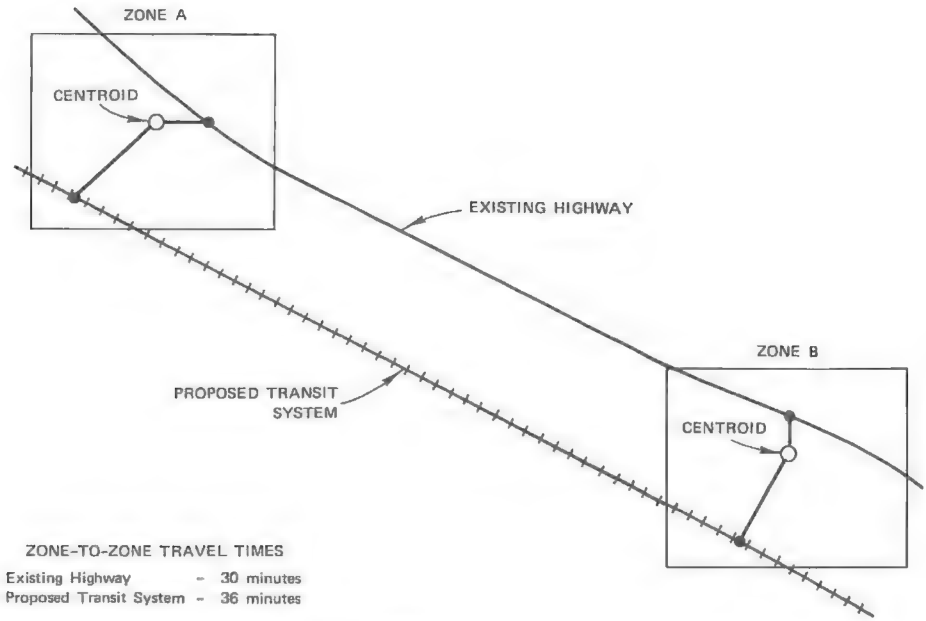

Figure 2. A hypothetical highway-transit modal split.

transit, then, 20 percent of the travelers would take 36 minutes to travel by transit, and the benefit-cost analyst would compute a 6-minute disbenefit.

In actuality, the travelers who would be most inclined to use transit would be those whose origins and destinations are close to the transit stations in the lower left corners of the zones. These travelers would actually experience a benefit because of easier access to transit than those in other parts of the zones. This benefit should be recognized.

In areas where the geographically larger suburban zones are expected to experience most of the population growth over the period of the projects, the calculation of a disbenefit in travel time can lead to substantial errors. The errors can be even greater when it is expected that the proposed transit system will have an effect on the geographical distribution of the forecast growth of population and economic development of a zone. When the zone centroid is held fixed in location over a number of plan alternatives, and when pronounced land use differences can be expected, the problem becomes more serious. In practice this problem can be alleviated somewhat by judicious design of zone boundaries and selection of access times. Otherwise, manual adjustments of the data may be required.

Even with judicious design of the zonal system, however, another inconsistency must be guarded against if modal split equations are developed separately from benefit-estimating equations. The two should be developed together, because the value system of the individuals making a choice between private automobile and transit can be measured to provide a basis for modal split and to gain insight into value parameters that should be used in estimating benefits. For example, a consistent means can be devised for relating the way in which individuals trade off time and money in choosing modes and for measuring the value of travel time savings.

MEASUREMENT OF MOTOR VEHICLE RUNNING COSTS

In conducting benefit-cost studies of both transit and highway improvements, many investigators have not been able to take into account the fact that motor vehicle running costs vary significantly with operating conditions. These costs vary as a function of

speed and acceleration and deceleration; thus, as new facilities result in less congestion, higher speeds, and less stop-and-go driving, costs will change.

Data on the cost variations caused by these factors have been available for some time (7) and more data are in process of being developed (8). Although observed data on speed change cycles are limited, there is no reason why approximations should not be incorporated into the estimates of motor vehicle running costs. Such a procedure is believed to be far sounder than using a single value per vehicle-mile (such as the national average published by the U. S. Bureau of Public Roads) that masks all differences in road types, congestion, and speeds. In a recent series of 117 highway economy studies (chiefly for new freeways), inclusion of these considerations resulted in almost all projects being economically attractive solely on the basis of savings in motor vehicle running costs, and inclusion of time savings added even more to their attractiveness.

As an additional point, in recent transit studies the study teams have sometimes not incorporated the fact that, when travelers are diverted from automobile to transit, congestion on existing highways is relieved and both time savings and reductions in motor vehicle running costs are likely. In one recent rapid transit study, such reductions in running costs amounted to 7 percent of the total travel benefits.

FACTORING FROM DAILY SAVINGS TO YEARLY SAVINGS

Although it would seem obvious that daily savings for work trips should be factored to annual amounts based on the number of work trips per year, such a procedure has not been followed in some studies. In one report, daily commuter trip cost and time savings were multiplied by 365 to arrive at yearly savings. In another report, the method of factoring cannot be understood; apparently, 95.4 days per year were used to factor time savings, 437.5 days per year for operating cost savings, and 691.7 days per year for parking cost savings.

For purposes of developing complete patronage, revenue, and benefit data, it is necessary to consider all times of day. Because the amount of travel and the degree of congestion change during the day, it is appropriate to consider dividing the day into a number of segments or otherwise to make recognition of such variations (6).

ECONOMIC VALUATION OF NONECONOMIC FACTORS

Most benefit-cost analyses in recent years have recognized that many effects of highway and rapid transit investments fall into the qualitative class, or into the quantifiable but not costable class. However, the bent of most benefit-cost analysts is to try to reduce as many effects as possible to dollar terms. In some cases, overzealous analysts have taken "stabs" at dollar values without a firm basis and even, in the worst cases, without stating any rationale for their estimated value.

In one study, improvements in urban life-style were discussed at some length. Under this category, subjects such as the effects on the nondriver, the increased range of choice, the preservation of open space, and the potential for rapid transit use as a standby mode of transportation were discussed. Then, a value for life-style benefits of \$25 million per year—equal to \$2.75 per capita per year—was assigned without any quantitative basis.

In another study, an analysis was conducted of the gains and losses to the tax base. Gains resulting from increased development intensities were estimated on a station-by-station basis, and losses were computed directly from right-of-way requirements. The net gain in tax revenues was estimated at \$426.6 million. Although no mention is made of the fact, it is certain that some of the increased development around stations would otherwise have located elsewhere in the region. No basis was given for an arbitrary conclusion that ". . . Twenty-five percent (or \$106.6 million) of these tax revenues is assumed to be a net increase to the Region and directly attributed to the impact of rapid transit." This total was not insignificant; it amounted to 13 percent of the total claimed net benefit.

Although it is difficult to argue that, in these two examples, a zero dollar value can be claimed for the items, the arbitrary assumptions themselves can certainly be

challenged. More often than not, however, they go without challenge; the professional judgment of the analyst stands. Nevertheless, in the interests of providing an unbiased view, the analyst should disclose as much as possible of the facts that led to a choice, and clearly state that the value assignment is based on his judgment.

TREATMENT OF UNCERTAINTY

Although this author strongly recommends the inclusion of a formal evaluation procedure as a necessary part of an overall transit feasibility study, it should be clearly pointed out to local officials and the general public that the nature of benefit-cost analyses is much different from that of engineering analyses. Benefit-cost studies depend on forecasts of the future, on computer analyses that are only rough simulators of actual travel conditions, and on value measurement procedures that are approximate at best. Under these conditions, potential uncertainties should be analyzed as an integral part of the overall study, and the results of the analysis should be communicated in the written report.

One approach is to make estimates of important variables not only on a most-likely basis, but also on a 10 percent-90 percent basis (values for which there is only a 10 percent probability that the actual value will be greater or less than the estimated value). Then the three variations should be followed through the analysis to determine whether the conclusion would be changed. Another simple approach is to determine what value each important variable would have to take in order for the conclusion to be changed, which is a form of sensitivity analysis. Unfortunately, few benefit-cost studies in the literature have gone to the trouble of conducting an analysis of the effects of uncertainty.

INTERPRETATION OF BENEFIT-COST RATIOS

Some benefit-cost studies have made great play in citing the ratio of benefits to costs as an indicator of the degree of goodness of a project. Statements such as ". . . will achieve a benefit-cost ratio of well over 3:1 by 2020 . . ." and ". . . returns $1.31 for every dollar invested . . ." imply that the higher the ratio, the better the project. Although such an implication is generally true, it should be recognized that the only correct use of the benefit-cost ratio in choosing between two mutually exclusive alternatives is to determine whether or not the ratio exceeds unity.

By choosing different methods of computing the ratio of benefits to costs, it is possible to derive significantly different values of the ratio. Consider a hypothetical project with four items of cost as follows:

Item	Present Value
Transit investment cost	$1.0 billion
Transit maintenance and operation cost	$0.4 billion
Items of increased private cost	$0.5 billion
Items of decreased private cost	$3.0 billion

Under one method of computation, the ratio is 2.1:

$$\frac{\text{Cost Changes Due to the Investment}}{\text{Investment Cost}} = \frac{2.1}{1.0} = 2.10$$

Under another method, the ratio declines to 1.78:

$$\frac{\text{Private Costs}}{\text{Public Costs}} = \frac{2.5}{1.4} = 1.78$$

And under a third method, the ratio is 1.58:

$$\frac{\text{Items of Decreased Cost}}{\text{Items of Increased Cost}} = \frac{3.0}{1.9} = 1.58$$

What is clear is that the public, not informed of the meaning of the benefit-cost ratio, may consider a project that will return "over $2.00 for each $1.00 invested" to be more desirable than a project that will save them only a bit more than $1.50 for every dollar. What is important is that the project should be considered favorably in terms of dollar-valued benefits and costs and that the net excess of benefits and costs is $1.1 billion.

Another crucial point with regard to the benefit-cost ratio is the need to use incremental ratios when comparing multiple alternatives. Although this point is documented exceedingly well in the literature, it is still overlooked in some studies.

CONCLUSION

The conduct of benefit-cost studies of transit systems requires not only a fundamental and clear recognition of the various points of view that can be taken and a careful structuring of alternatives, but also careful attention to detail. The recommended framework for such evaluations is to recognize that an improvement in transportation will affect different members of the community differently; thus, the differential effects should be measured separately to the extent possible. The framework should include all appropriate effects, both those that are beneficial and those that cause disbenefits, in both traveler effects and community effects. It should carefully avoid errors of double-counting. It should place dollar values on those effects that can be reasonably reduced to such a basis, measure in a quantitative manner those effects that cannot be valued in dollar terms, and analyze in a qualitative manner those remaining effects that cannot be measured quantitatively.

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Evaluation of a Bus Transit System in a Selected Urban Area

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The objective of this study was the investigation and evaluation of a bus transit system as a reasonably acceptable and economical alternative to the construction of additional highways in medium- to large-sized urban areas. In a selected urban area, the location and magnitude of the forecast year peak hour vehicular overloads on the existing and committed highway systems were determined. Two alternative transportation systems were designed to reduce or eliminate the forecast year overloads—one automobile-oriented and the other bus transit-oriented. Through the use of a modal split model developed as part of the study the ability of each system to relieve the vehicular overloads on the highway system was evaluated. The costs of each system were estimated. It was concluded that bus transit was capable of alleviating peak hour overloads on urban freeways. Based on the findings of the study, bus transit systems were considered a viable alternative to increased urban freeway construction.

•THE COMBINATION of widespread single family home-ownership and industrial technological changes is bringing about the development of vast, low-density areas on the periphery of every urban area in the United States. Conventional public transit cannot compete effectively with the automobile in these generally affluent, low-density areas; and thus most travel to and from origins and destinations in these areas is by automobile. Retention of many attractions, particularly employment, in the high-density central areas causes peak hour traffic congestion, partly from private automobiles originating in the low-density suburban areas. The traffic stream toward the central business district (CBD) is composed of personal automobiles destined to, beyond, and short of the CBD and trucks, taxis, and vehicles originating outside the urban area.

Demands for more streets, highways, and parking facilities, the only alternatives to transit, are exceeding the fiscal and spatial resources of some urban areas. Any solution to future transportation problems, short of introducing revolutionary changes or burdensome restrictions on the growth and development of urban areas, must either provide more transit service or more highway facilities or, more realistically, a combination of both, using the best characteristics of each alternative to provide an optimum balance between user needs and cost of building and operating the facilities.

During the last two decades, bus transit systems have experienced lower patronage, higher fares, reduced service, and still lower patronage. Recently, however, there has been a significant countertrend in patronage, indicative of the bus transit system's promising future role in the transportation pattern of cities in the United States. Transit ridership has increased in areas featuring express bus service to congested business and commercial centers and on special, premium fare, door-to-door services. Similar increases have been noted in communities with aggressive and effective mass transit marketing and public relations programs.

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The success of a bus transit system in any community depends on the degree to which it can satisfy the transportation needs of the community and its residents. The development of an effective system, therefore, must be founded on the social, economic, and political goals of the community and must be backed by the willingness of the community to provide the determination, leadership, and resources to meet these goals.

OBJECTIVES OF STUDY

The study, conducted by Peat, Marwick, Mitchell and Company under contract to the U.S. Bureau of Public Roads, represents an attempt to remove some of the uncertainty about the economic viability of bus transit to meet the rising demand of travel in medium- to large-sized urban areas. The objective of the study was the investigation and evaluation of a bus transit system as a reasonably acceptable and economically competitive alternative to the solution of current urban travel problems. To achieve this goal, two transportation systems, one automobile-oriented and one bus transit-oriented, of designed equal utility were evaluated to determine which was the lower cost system.

In order to further ensure that the highway and bus system components were of comparable utility, a relatively uncongested flow was established for both automobiles and buses on the highway network during the peak hour, and most bus passengers had seats for the major portions of their trips. It was felt that these two conditions, both technologically obtainable (at an estimatable cost), would ensure nearly equal comfort and convenience for all travelers.

CHOICE OF TEST SITE

The metropolitan area of Baltimore, Maryland, was selected as the test site to compare the alternative systems. Baltimore was chosen because it was considered typical of many cities with regard to its social, physical, and economic development and because data were available.

The findings of this study, however, are not to be construed as a plan of action for Baltimore because the study differed from a typical analytical transportation planning study in a number of fundamental ways. Initially, there was no "feedback" of information on how the proposed transportation plan would affect land use and subsequent trip generation and distribution, which might, in turn, affect use of the transportation system. Furthermore, no consideration was given to a fixed-rail transit system because the principal goal was specifically the evaluation of a bus transit system, not the evaluation and selection from a number of different competing systems. A fixed-rail system, one possible alternative, has been recommended recently for implementation in Baltimore. No inference, therefore, should be drawn concerning the relative advantage or disadvantage of a competing rail transportation system, specifically for Baltimore.

DESCRIPTION OF STUDY

The method for evaluating bus transit systems is similar in concept to the simulation processes used in urban area studies. The steps typically include land use forecast, trip generation, trip distribution, modal split, network assignment, and evaluation. The study accepted the first three items (land use forecast, trip generation, and trip distribution) as given. All information utilized, including the forecast of trip interchange patterns, was based on data from the Baltimore Metropolitan Area Transportation Study (BMATS) conducted in 1962.

The study was divided into five phases, as shown in Figure 1. A description of the activities in each phase follows.

Phase 1—Determination of Travel Overloads

The determination of travel overloads required identification of the location and magnitude of deficiencies in a future, "committed" highway system, as well as the

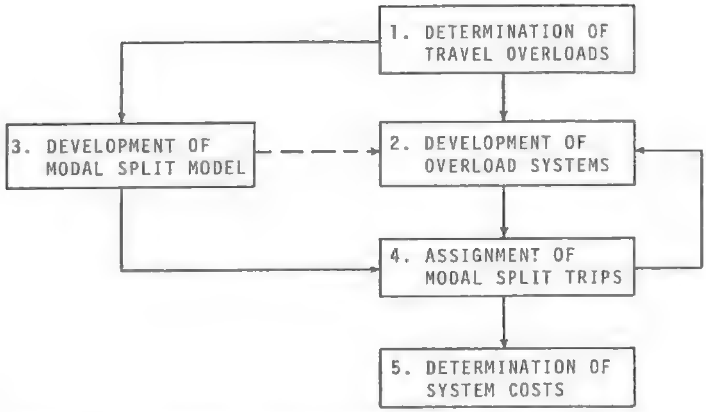

Figure 1. Study approach for the evaluation of a bus transit system in a selected urban area.

identification of any part of the system that might be "under-utilized". The accomplishment of these tasks required some knowledge of how individuals will act and what travel mode choices they will make in the future.

An initial step in determining travel overloads was the development of a special overload trip table. This table was produced by subtracting the number of 1962 transit trips from the projected 1980 total number of person trips. The implications of this assumption were that the existing transit system would attract its present ridership in the future and that the remaining travelers would use automobiles. This assumption was not necessarily true, nor was there any assurance that the present transit system would attract as many travelers or the same patterns of travelers once the committed highway system was operative. This rough approximation seemed less than desirable, but the emphasis was on identifying corridors or areas of overload rather than on exacting values of roadway volumes. It was felt that this procedure would produce a satisfactory picture of travel overloads for the purpose of developing new bus and automobile systems without preparing extensive preliminary modal split information.

For this study, it was desirable to develop a complete understanding of travel behavior and its associated characteristics, and to analyze and properly evaluate differences in alternative investments. Two areas of fundamental concern in the scope of research—congestion and cost—were related to travel occurring over different time spans. Because congestion and associated problems of capacity and delay are generally present during the peak periods of the day, their characteristics usually can best be identified by observing traffic during the "journey-to-work" periods of any weekday. Conversely, costs and revenues should be derived using periods of time that exhibit cyclical travel patterns. Consequently, 24-hour periods were established as the time spans used to study problems of costs. As a result, 2 different hours were selected from a weekday to represent the entire day for data collection and analysis purposes.

The objective of Phase 1 was the identification of trips involved in areas of future roadway congestion during a typical hour of peak and off-peak travel conditions. The attractiveness and success of the proposed new bus services were evaluated for an entire day (peak and off-peak hours) by expanding the travel patterns during these hours to encompass the whole day, based on the percentage of the day they represented.

The peak and off-peak overloads were determined by assigning the overload trip tables to the networks and analyzing the major travel corridors for overload conditions. Several major radial corridors were observed to be significantly overloaded. These corridors approached the CBD from the north, northwest, northeast, east, south, southwest, and west. In addition, a less serious overload was observed on a single crosstown corridor across the north part of Baltimore.

Phase 2—Development of Overload Systems

In Phase 1, the pattern and size of overload areas became apparent. This information was used to formulate designs of two competing alternative transportation systems to solve the overload problem. One system, the automobile-oriented system, consisted of the unimproved transit system existing in the base study year (1962) and a greatly improved highway system designed to alleviate the expected future year peak hour overloads. The other system, the bus transit-oriented system, consisted of an improved transit system and the existing and committed highway system. The design of the improved highway system and the improved transit system is described in the following paragraphs.

Improved Highway System—The determined overloads indicated that an improved highway system was necessary to provide capacity for the peak hour vehicular demands. The most costly highway improvements to alleviate peak hour overloads were required in the inner city or where the high density of trip ends and the funneling of other trips through a small geographic area caused overloads.

Improved Transit System—Today's standard buses reflect vast improvements over earlier equipment. Their wider seats, wider doors, easier access, improved visibility, and air conditioning enhance passenger comfort and convenience. Modern heavy-duty engines and improved acceleration characteristics permit buses to maintain their position in mixed-flow traffic on streets and highways.

The design of the improved transit system was largely concerned with the extra-vehicular considerations of routes, schedules, and the minimization of walking, waiting, and transferring times. In seeking to maximize service and patronage, initial design of routes and frequencies used all service techniques that held promise of realistic success in the Baltimore environment and that could be accomplished within the limits of present technology, labor procedures, and life-styles. These service techniques are described in the following.

Revision of existing service—The integration of transit operations in the area was considered a prerequisite to maximizing service and patronage. The design of an improved transit system was undertaken assuming integration of bus operations in Baltimore and suburban areas. The suburban bus company feeder lines, an outgrowth of suburban expansion, were mainly integrated with principal radial bus routes. Through this integration, additional fares and transfers, the antithesis of maximum service and patronage, were removed wherever feasible.

Supplemental express service—The development of supplemental express service was also considered an essential element to maximizing service and patronage. Supplemental express service was designed to reduce the collection phase in time and space and to expedite movement to the destination over the shortest time path, using the following techniques:

1. Exclusive bus lanes or ways, which are special lanes either on or immediately adjacent to a freeway or on other special rights-of-way that are permanently set aside for the use of buses. These lanes, by providing an exclusive right-of-way for public transportation vehicles 100 percent of the time, allow buses to achieve service comparable to that of a rapid rail facility.
2. Reserved bus lanes, which are freeway lanes set aside for the exclusive use of buses only during peak travel hours, but can be opened for general vehicle use during off-peak hours.
3. Reversible lanes, i.e., all or part of the reversible section of a freeway providing for the peak hour imbalanced vehicular flow that may be reserved for buses.
4. Metering or preferential entry, which involves controlling or "metering" the flow of vehicles onto a freeway to preclude or diminish the over-utilization of the freeway that results in reduced travel speeds. Coupled with this is preferential entry, in which a bus bypasses the queue of vehicles awaiting entry onto the freeway.

Most supplemental express routes were radially oriented and CBD-destined. In addition, several outbound and circumferential express routes were provided to significant employment areas. Even though no outbound highway overload was observed, the

outbound routes represented provision of service to a significantly high number of persons in industrially oriented Baltimore with the same equipment operating inbound to the CBD, which would otherwise return to the suburban areas empty. Within the CBD, some express service lanes were routed on reserved street lanes during peak hours to facilitate loading and unloading and to improve speed.

Revision of fare structure—The fare structure was revised to reflect the simplicity of the integrated bus operations. The existing (1962) transit fare structure contained, in effect, 88 different districts. The revised structure contained only 20 fare districts but essentially maintained the basic fares of the previous structure. Transfer charges and the second fares required when transferring between companies were eliminated. A 25-cent base fare for intradistrict travel was established. Generally speaking, at each district boundary crossing, the fare was increased by 10 cents, but circumferential travel, when performed over circuitous radial routes, was not penalized, and the maximum fare was set at 75 cents.

Increase in service frequency—Patronage potential and overload considerations indicate that transit volume, largely on radial lines, must increase by 80 percent in 1980, compared with the 1962 volume, if bus transit is to absorb the highway overload. Accordingly, an 80 percent expansion in frequency of service in radial corridors was planned. The portion of this expansion in excess of the service frequency of the supplemental express service was applied to the existing service in each radial corridor. The expansion in frequency was usually near the outer end of the existing radial routes, as extended by integration of suburban feeders. Of course, this expansion of service frequency was also applied at the maximum load points near the CBD.

The level of service on crosstown (circumferential) lines was improved by increasing service frequency. The increase was approximately 50 percent on the crosstown lines. The revised levels of service at major transfer points were reviewed for optimum "wait time" for interline transfers. In most instances, the estimated wait time (half the headway on the line to which transfer is made) was less than 5 minutes in the peak hour.

Following the preliminary design of the supplemental express service and the revisions of existing service for peak hour operations, the off-peak service was reviewed for improvement in accordance with the development concept. Off-peak service was established on most of the supplemental express lines and was increased on the revised existing system. The planned frequencies were about a third of peak hour frequencies, but not less than hourly.

Downtown distribution plan—In developing rights-of-way for transit vehicles, downtown bus terminals and reserved lanes on surface streets were considered as the basic alternatives. Door-to-door access, travel time, and local customs were the key service considerations in designing the downtown distribution plan.

Phase 3—Development of Modal Split Model

A modal split model was developed for Baltimore, expressing people's choice of travel mode. This model basically consisted of a number of diversion curves for each combination of transit-versus-automobile cost strata and dwelling-unit income strata for the trip purposes of work, school, non-work and non-school. Considerable success utilizing this technique has been achieved in analyzing data from cities such as Philadelphia, Boston, Washington, Toronto, Edmonton, and Winnipeg.

The standardized procedure for calibration and validation of the model considered the basic determining factors to be (a) relative travel time via public transit and private automobile expressed as a ratio, (b) relative travel cost via public transit and private automobile expressed as a ratio, (c) economic status of the trip-maker expressed as median income per worker, and (d) trip purpose and time of day. The basic relationships expressed modal split as a percent of transit ridership against the travel time ratio.

The other variables (relative travel cost and income) were considered as stratification variables in the development of the diversion curves. The relative travel cost variable was defined as the ratio of out-of-pocket travel cost by public transit divided by the out-of-pocket travel cost by private automobile.

Phase 4—Assignment and Analysis of Modal Split Trips

In Phase 4, assignments were made to the transit and highway networks using the forecast trips of the automobile-oriented and bus transit-oriented transportation systems. The networks were balanced by tailoring the facilities designed in Phase 2 for the overload systems to just meet the demand. Highway networks were adjusted by adding or deleting lanes or links, or both. The transit network was adjusted by shortening or lengthening routes and selecting service frequency to conform to the transit load. The route structure of the balanced, improved transit network is essentially the same as that designed in Phase 2.

Analysis of Automobile and Bus Transit Highway Facilities—The bus transit-oriented system attracted approximately 16,000 more persons to the transit system in the morning peak hour than the automobile-oriented system. The difference was concentrated mainly in and near the CBD and alleviated the overload on the existing and committed highway networks in this area. The bus system was not capable of alleviating the overloads that occurred on portions of the Baltimore Beltway or on some outlying highway facilities because of the poorer competitive position of bus transit in areas having low density and highly dispersed travel patterns. Likewise, the improved system was unable to alleviate highway overloads caused by trucks or other vehicles that originated in or were destined to areas outside the metropolitan area. This was the case on the Baltimore Inner Harbor Tunnel, a facility heavily loaded with external and truck traffic. The most pronounced difference between the two alternatives was in the vehicle volumes approaching the CBD.

Major new highway facilities and improvements to existing facilities were proved necessary for the relief of peak hour overload in and near the CBD in the automobile-oriented system. Use of special bus facilities, such as ramps and grade separations, proved beneficial in speeding buses around or over traffic or in a more direct line to their ultimate destinations. These facilities carried loads of between 2,500 and 5,000 persons per hour—the equivalent of 50 to 100 busloads in the peak hour.

Express buses were designed to be routed on freeways into the CBD. The busloads on the densest sections of these radial freeways were also in the range of 50 to 100 in the peak hour. Because of the relatively free flow conditions that were designed for the highway networks, the buses were able to operate in mixed traffic. Exclusive or reserved lanes were not necessary or warranted because the busloads were fairly light, and the time savings over the remaining traffic was small because of the slight speed differential and the short distance traveled on the freeway.

Analysis of Bus Systems—For the autombile-oriented system, 614 fifty-passenger buses were required; the bus transit-oriented system required 900 such buses. By way of comparison, the base year (1962) bus fleet consisted of the equivalent of 812 fifty-passenger buses. The highest peak hour busloads were observed on corridors of travel approaching the CBD. The highest load on any of these corridors was 8,750, with the other corridors ranging from 5,000 to 5,600.

The patronage on most of the supplemental express service routes was fairly good. The most heavily patronized express routes were the radially oriented, CBD-destined routes. Some of the outbound express routes from the CBD to high-density employment sites were also well patronized. Others were not successful for reasons not apparent, such as the circumferential express route. Where a new express route competed for the same business as the existing local route, the express was more heavily patronized, capturing most of the business of the local route.

Local routes operating without competition from express routes in the bus transit-oriented system showed somewhat higher patronage than the same local route in the automobile-oriented system. This was probably due to the relatively improved linking of transit service in the bus transit-oriented system and to the simplified fare structure.

Phase 5—Determination of System Costs

The annual cost method was chosen as the procedure for economic comparison of the two alternative systems. The results were obtained by comparing the annual costs of each alternative. In this manner, each separable increment of proposed investment

was considered independently. Based on the theory of capital rationing, which recognizes that resources are and will remain scarce in relation to demand, the preferred solution among alternatives of equal utility was the one incurring minimum cost.

Travel demand, which was projected from the 1962 base year inventory to 1980, formed the analysis period for the study. The systems to be evaluated during this period were defined as the existing and committed highway networks, the existing transit facilities, and additional highway and transit facilities, improvements, appurtenances, buses, and services necessary to meet study objectives.

The uniform annual costs for the 1962-1980 period were computed for each year using an annual discount rate of 6 percent and were expressed in 1966 dollars. For comparison purposes, an annual discount rate of 12 percent was also examined, but it did not produce significantly different results. These costs are given in Table 1.

Public Sector System Costs—Public sector user costs were composed of the following: (a) capital investment, including the costs of construction and rights-of-way for highway facilities, traffic engineering improvements, parking facilities, and fixed transit facilities, as well as those for transit vehicles; (b) plus operating and maintenance costs for highway facilities, traffic operations, and transit vehicles; (c) plus revenue and taxes for both public and private operations; (d) less the remaining service life, which was equivalent to the remaining value of investment as of 1980 for the capital items. Straight-line depreciation, 20-year life, and 20 percent net salvage value for facilities, and a 15-year life and 5 percent salvage value for buses were assumed. It can be seen from Table 1 that only a small economic benefit in the public sector costs was realized from the bus transit-oriented system. The difference between each alternative was so small in relation to the total community costs that no inference was drawn as to which system should be recommended solely on a public sector cost basis.

Private Sector User Costs—In the development of private sector user costs for improved transit systems, the transit fares, automobile ownership costs, and automobile operating costs (including parking fees, tolls, and accident costs) were considered. The uniform annual cost estimate for private automobile operating costs, expressed in 1966 dollars, was $480.3 million for the bus transit-oriented system and $493.1 million for the automobile-oriented system. Comparing these figures with those in Table 1, it can be seen that the magnitude of automobile operating costs dwarfed all other quantifiable monetary transportation costs. It is also apparent that there was an almost negligible difference of less than 3 percent in the automobile operating costs of the two systems. A majority of automobile travel took place in off-peak hours and in areas not affected by congestion and was practically unaffected by the improved bus transit system, which was designed to attract the peak hour overloads in the central business district. The absence of a significant difference indicated the continued overwhelming reliance on the private automobile for most travel, especially in off-peak hours and in low- and medium-density areas. Even though automobile operating costs were the dominant component of all urban transportation costs, they are ironically the least perceived of all costs.

TABLE 1

UNIFORM ANNUAL PUBLIC SECTOR COSTS OF ALTERNATIVE TRANSPORTATION SYSTEMS, 1962-1980

(In Millions of 1966 Dollars at 6 Percent Annual Interest)

Item	Bus Transit-Oriented System		Automobile-Oriented System	
Capital Cost				
Highway facilities	90.5	92.1	105.1	108.8
Parking facilities	1.6		3.7	
Transit facilities	1.4	3.5	0.0	1.3
Transit vehicles	2.1		1.3	
Subtotal	95.6		110.1	
Operating and Maintenance Costs				
Highway facilities	32.8	35.7	33.0	37.9
Parking facilities	2.9		4.9	
Transit facilities	0.2	25.9	0.0	20.0
Transit vehicles	25.7		20.0	
Subtotal	61.4		58.3	
Remaining service life[a]				
Highway facilities	35.9	36.5	41.7	43.3
Parking facilities	0.6		1.6	
Transit facilities	0.6	1.1	0.0	0.3
Transit vehicles	0.5		0.3	
Subtotal	37.6		43.6	
Total	119.4		124.8	

[a]To be deducted from capital, operating, and maintenance costs.

An estimate of the annual transit profit or subsidy required for the bus transit system indicates that the automobile-oriented transit system was able to sustain a slight profit ($2.2 million), whereas the bus transit-oriented system operated at a deficit of $400,000. The automobile-oriented transit system, which did not have the goal of attracting the peak hour overload, operated at relatively higher load factors in the peak hours, had a smaller transit fleet maintenance cost than the bus transit-oriented system, and operated with relatively greater efficiency during the off-peak hours.

The potential for decreased automobile ownership because of increased transit ridership was approximated by the decrease in home-to-work automobile trips for the bus-oriented system compared with the decrease for the same trips in the automobile-oriented system. The extent to which this potential reduction could be realized is problematical. The question essentially concerns the effect of relative transit accessibility on automobile ownership. A regression analysis of automobile ownership in 20 major cities indicated that approximately 735,000 automobiles were estimated to be owned by the Baltimore study area residents under the automobile-oriented system and approximately 670,000 under the bus transit-oriented system, thus resulting in a net savings of the costs of owning about 65,000 automobiles for the bus transit-oriented system. It can be seen that there is approximately an 8 percent savings in automobile ownership costs for the study area residents in 1980.

Community Impact Costs—In addition to considering costs associated with the two alternate transportation systems and those associated with the users, there are impacts on the region and its inhabitants that must be taken into account. These impacts concern social values, environmental values, the general economy, and the use of land. In general, these community impact costs were largely intangible and could not be directly or objectively reduced to quantifiable monetary terms. However, the framework of generally agreed upon community goals should be established, and alternative transportation systems should be evaluated objectively in light of fulfilling these goals.

CONCLUSIONS

Based on the findings of this study, bus transit systems should be seriously considered as an alternative to the construction of additional highways in medium to large urban areas. The following conclusions were drawn from the case study and are recommended for consideration by those who may plan and implement bus transit systems in the near future:

1. Bus transit is capable of alleviating peak hour overloads on urban freeways. Radial freeways in the densest part of the city can be relieved of peak hour demand to the degree where no additional community resources are required in the near future to provide additional capacity. Bus transit is not able to compete effectively in less dense areas or where transit desires are widely dispersed, nor is bus transit able to relieve to a significant degree the overload from highway facilities that are heavily loaded with traffic not susceptible to bus transit such as through, external, or truck traffic.
2. In the urban area studied, relatively free flow was designed for the highway network during the peak hour. Exclusive rights-of-way, however, are distinctly advantageous for bus travel to maintain its competitive position. Either "busways" or preferential entry to metered or reserved freeway lanes during peak hours is recommended to speed bus transit around congested peak-period traffic.
3. In view of the relatively light busloads observed on the most densely traveled sections of typical urban freeways, it appears worthwhile to recommend that other special vehicles, such as high-person-occupancy automobiles, be allowed to use exclusive busways or reserved freeway lanes during the peak period in order to take advantage of the available vehicle capacity.
4. The existing and committed highway systems developed in most cities, primarily under the impetus of the Federal-Aid Highway Act of 1956, are the basic ingredients for the successful operation of a viable bus transit system. These high-speed paths represent the backbone of a competitive bus transit system route structure. Direct and rapid access from suburban areas to the CBD is extremely important. Where no such paths exist or where the bus is severely disadvantaged by operating at typical

peak period forced-flow conditions, the competitive position of bus transit suffers. Completion of certain essential links in some cities' freeway systems is recommended in order to provide direct and speedy bus routes. Once the basic freeway system is constructed, however, bus transit on the basic system can eliminate the need for additional links or lanes, in many areas, by being able to accommodate peak hour overloads.

5. Analysis of the economic findings in this study revealed that the costs of the bus transit-oriented and the automobile-oriented systems are nearly equal on a direct quantifiable monetary cost evaluation. Within the range of costs studied and methodology of evaluation used, no inference can be made as to which system is to be recommended based solely on direct quantifiable monetary considerations.

6. Analysis of the noneconomic findings, however, indicated that the advantage seems to be to the bus transit-oriented over the automobile-oriented system. The former system, as compared to the latter, is considered by the authors to provide more accessibility to more people, promote more heterogeneous social contacts, be less disruptive of the community values, and be more aesthetically pleasing.

A Model for Highway Needs Evaluation

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The highway needs evaluation model is designed to provide the policy determination of the suitable level of highway investment in a large, primarily urbanized region and the allocation of this investment to subareas based on a common set of social and economic values. The influence of variations in expressway supply on the volume and distribution of travel and certain measures of travel cost, specified through regression analyses, is used to evaluate the overall effect of increasing the level of expressway supply. It was found that increases in expressway supply lead to increases in total travel volume and reductions in average travel cost per mile. This benefit to the highway user is balanced against the costs of increased supply in order to select the level of capital investments that provide maximum satisfaction of the established regional objectives. Sensitivity analysis is used to consider the effect, in terms of the investment supply level, of changes in the values placed on specific objectives included in the model. Those values to which the results are most sensitive are the value of travel time and the opportunity cost of capital. A brief discussion of suitable directions for future research and development is included.

•ONE OF THE KEY FUNCTIONS of the regional planning process is the determination of the need for capital investment in public systems. The selection of an appropriate level of investment in highway facilities is particularly significant because of the important effect the quality of the highway transportation system has on the development of the region and in view of the large portion of public capital that is allocated to highway construction.

This paper describes a model for determining a suitable level of highway investment in a large, primarily urbanized region and the allocation of this investment to subareas within the region based on a common set of social and economic considerations. The model offers the following advantages as compared to existing methods:

1. It requires a minimal amount of travel information.
2. The objective function may be modified to reflect the values of the region under study.
3. The importance of different objectives on the final proposal may be tested.
4. The objective function provides a basis for making trade-offs between the allocation of resources to high-density areas where costs and benefits are high and low-density areas where costs and benefits are low.
5. A general level of requirements, which will serve as a framework for development of more specific proposals, can be established early in the planning process.

The model is described in detail in the following sections of this paper.

HIGHWAY PLANNING OBJECTIVES

It has been reasoned that the logical objective of a transportation system is to assist society to achieve its basic needs and objectives (1). A suitable analytic approach is to

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consider highway planning decisions in a framework of providing high-quality travel service with an emphasis on functional efficiency and avoidance of negative social impacts.

The first stage in the process of developing an operational objective function is to list the relevant objectives:

1. To provide high-quality travel service (TRAV BEN);
2. To maintain a high level of functional efficiency, that is, (a) reduce travel time (TT), (b) reduce the number of accidents (ACC), (c) reduce vehicle operating costs (VEHOP), (d) reduce capital investment in highways (CCOST), and (e) reduce highway maintenance and operating costs (MCOST); and
3. To avoid or reduce negative social impacts such as (a) the disruption to communities and individual households caused by new highway construction (DISRUPT), (b) traffic penetration of local neighborhoods (TPLN), and (c) air pollution and traffic noise (POLL).

There are conflicts between some of these objectives. One method of resolving these conflicts is to assign weights to each objective and to define the overall highway planning objective as maximizing the weighted sum of these individual objectives. There are certain problems involved with any attempt to apply a universal value to some of the stated objectives. Nonetheless, such judgments must be and are being made daily. The use of a common set of values is justified in order to compare the relative needs of differing areas; the use of local values might be required in more specific studies.

In general form, the objective function can be expressed as

$$\text{Maximize}\left(\text{Travel Benefit} - \sum_{i=1}^{N} w_i C_i\right) \tag{1}$$

where C_i is the ith cost of travel measured on an appropriate scale such as hours, dollars, or occurrences; and w_i is the weight assigned to the ith cost. This objective function is shown in Figure 1, where the objective is to select the level of highway supply that will maximize net travel benefit.

For the sake of simplicity and ease of interpretation, equivalent daily dollar values will be used as weights for the individual objectives. The effect of the use of different weights will be considered in the section on sensitivity analysis.

Travel time savings are valued at $6.00 per commercial vehicle-hour based on driver salaries, fringe benefits, and vehicle depreciation and at $2.50 per passenger vehicle-hour based on per capita income in the region. The value of commercial vehicle time

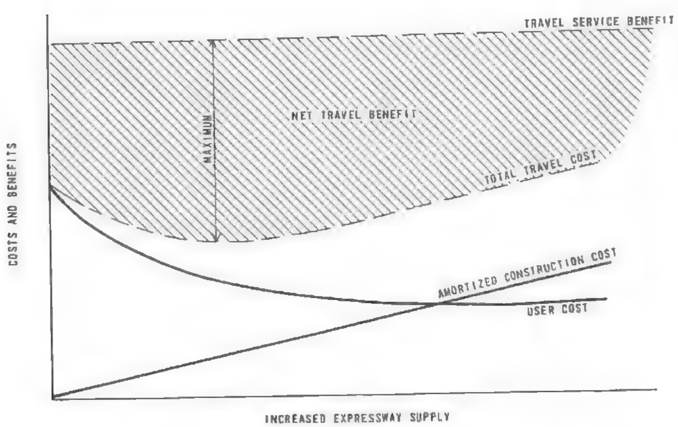

Figure 1. Highway planning objective function.

is obtained by adjusting the value of \$5.16 for the Middle Atlantic Region in 1965 (2) by 3.5 percent per year up to 1969 to reflect increased costs. Average hourly income of wage earners in 1969 is estimated at \$4.30. Distributing this income over the total population indicates a weighted average value of \$1.80. Assuming that the average automobile occupancy is 1.4 persons, the value of passenger vehicle time is estimated at \$2.50 per hour. Travel time savings are considered to be additive for valuation purposes; that is, all units of time savings will be valued at the same rate independent of their absolute size (2).

Average accident costs, \$1,470 per reported accident on expressways and \$925 per reported accident on arterials and local streets, were obtained by adjusting average per-involvement costs estimated for the Washington, D.C., area (3). An additional cost of \$325 is assigned to reported accidents on arterials and local streets to represent the frequent occurrence of low-cost unreported accidents. Vehicle operating and maintenance costs are estimated from mileage driven, average speeds, and free speed, using relationships developed by Winfrey (4) and Schneider (5).

Previous studies have shown the relationship between construction costs (including right-of-way) and the density of development in the surrounding area (6). For this analysis the average cost of expressway construction is estimated as a function of population density and interchange spacing. The construction cost (Fig. 2) varies from \$2 million per route mile in a rural area with interchanges spaced about 15 miles apart to \$45 million per route mile with a 1-mile spacing between interchanges located in the center of the region. The capital recovery factor of 0.1446 is based on an opportunity cost of capital of 10 percent per year, a project life of 25 years, and the assumption that annual benefits vary from 50 percent of the target year value in the first year to 150 percent in the 25th year. On a daily basis this factor becomes 0.000396.

Highway maintenance and operating costs are estimated at \$33,000 per mile of expressway per year, or approximately \$90 per mile per day. This cost is based on highway maintenance and traffic services, law enforcement and safety, administration, and miscellaneous services for state-administered highways in New York, New Jersey, and Connecticut from 1963 to 1967, as reported in "Highway Statistics" and adjusted to allow for cost increases in 1969.

The social objectives are more difficult to value quantitatively. However, their significance is such that reasonable effort should be directed toward the development of methods for measuring and evaluating the effect of changes in the highway system on these objectives. To the extent that this is not accomplished, these objectives must be considered subjectively in the preparation of final recommendations.

Of the three items of social impact listed, only one—disruption caused by new construction—is amenable to quantitative estimation for the purposes of this study. We will assume that this element can be partially measured from the unreimbursed costs of community relocation of all types. A recent study in Baltimore indicated that unreimbursed monetary costs average about \$3,500 for each relocated family (7). For simplicity, the unreimbursed relocation expenses for other private activities (stores, doctors' offices, etc.) and public activities (parks, schools, etc.) will be included by doubling the costs of household relocations (a very rough estimate) for an overall estimated equivalent cost of \$7,000. Furthermore, there are additional nonmonetary costs associated with relocations and community disruptions. It seems reasonable then to include some allowance for these costs (say, an additional \$3,000 per household for a total of \$10,000) based

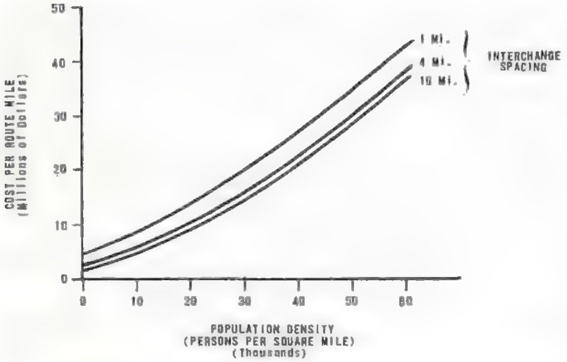

Figure 2. Construction and right-of-way cost per mile.

on the principle that individuals in the path of new highway construction should not suffer injuries as a result of programs designed for the benefit of the general public (8). Because of the one-time nature of relocation costs, they must be weighted by the same capital recovery factor applied to capital investment costs.

The number of household relocations is a function of the land area required for right-of-way and the population density of the area. Although efforts are made to avoid taking residential structures, in urbanized areas this can only be done at the sacrifice of other developed property.

The introduction of these weightings in the general objective function provides the following specific function for the Tri-State Region:

$$\text{Maximize} \begin{bmatrix} \text{Travel Benefit} - \$6.00\ TT_c - \$2.50\ TT_p - \$1{,}470\ ACC_E \\ -(\$925 + \$325)\ ACC_{AL} - VEHOP - 0.000396\ CCOST \\ - \$90\ RT\ MI_E - 0.000396 \cdot \$10{,}000\ HHREL \end{bmatrix} \qquad (2)$$

where

TT_c = total travel time of commercial vehicles,
TT_p = total travel time of private vehicles,
ACC_E = the number of accidents expected on expressways,
ACC_{AL} = the number of accidents expected on arterials and local streets,
CCOST = the initial cost of road construction and right-of-way acquisition,
RT MI_E = the route miles of expressway, and
HHREL = the number of expected household relocations.

This formulation provides a basis for estimation of the objective function except for the underlying benefit of highway travel, which is the most difficult to evaluate because of the lack of detailed knowledge of the benefits that accrue to individual highway users. Fortunately, this difficulty is not critical as long as the total benefit is assumed to be greater than the total user and nonuser costs. If the total volume of travel remains constant, the travel service benefit will remain constant and minimization of the weighted cost elements is equivalent to maximizing the objective function. If, however, the amount of travel increases (as will be discussed later), net benefits may be viewed in terms of consumer surplus.

In effect, this avoids counting any social benefit for the generation of additional travel based on the assumption that the benefits derived are just equal to or only marginally greater than the costs incurred when the trip becomes acceptable. However, further reductions in travel cost are applied to the generated travel as well as to the previously existing travel.

HIGHWAY TRAVEL DESCRIPTION

The satisfaction of individual objectives for any level of highway investment may be predicted through use of the highway travel description model developed for making such predictions for highway travel in the Tri-State Region. The model in Figure 3 is based on economic demand theory supported by observations of regular and repetitious travel behavior in the region and has the following general characteristics:

1. Vehicle-miles of travel can be predicted as a function of vehicle trip ends (origins or destinations) and the supply of expressways over any reasonable size area.
2. The ratio of vehicle-miles of travel to vehicle trip ends varies downward with increasing density but upward with increases in expressway supply.
3. The distribution of vehicle-miles of travel between different classes of facilities, although more sensitive to external factors, is also in the predictable range.
4. The proportion of travel on expressways increases as the supply of expressways is increased.
5. Travel on arterials and local streets decreases absolutely and proportionally as the supply of expressways is increased.

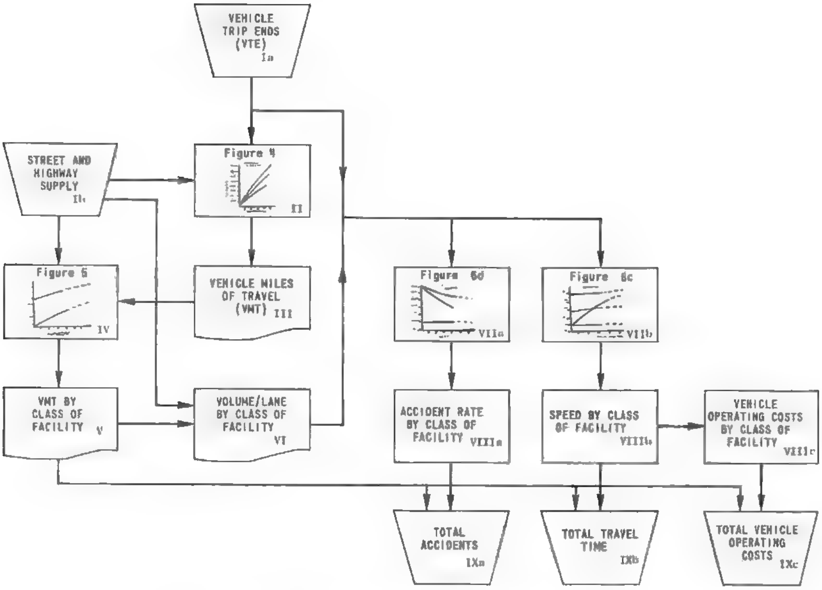

Figure 3. Highway travel description model.

6. Quantitative measures of performance, such as travel speed and accident rates, can be estimated from the loading on each facility class.
7. The descriptive ability is aimed at those characteristics that measure the degree of achievement of the objective function.

The first stage in the description of future highway travel requires the projection of vehicle trip ends. This projection is made by conventional techniques from previously established estimates of population, employment, household size, income, and automobile ownership.

The amount of travel that will actually take place on the streets and highways of the area, measured in terms of vehicle-miles of travel per square mile, can be estimated from this projection of vehicle trip ends per square mile by the following equation (Fig. 4):

$$\mathrm{VMT} = 56.0\ \mathrm{VTE}^{0.77} \tag{3}$$

where VMT is vehicle-miles of travel per square mile and VTE is vehicle trip ends per square mile. The root mean square error is 0.85.

Although Eq. 3 provides reasonable estimates of the total volume of motor vehicle travel, it is unsatisfactory in view of the lack of sensitivity (or elasticity) to variations in the supply of expressways. In general, an increase in expressway supply will cause a reduction in average travel cost and, if the demand for motor vehicle travel is not completely inelastic, will bring about an increase in the total volume of travel (9). The following structural equation was proposed to provide a degree of sensitivity to variations in expressway supply:

$$\mathrm{VMT} = A \cdot \mathrm{VTE}^{B}\ e^{(C\ \cdot\ \mathrm{PDS})} \tag{4}$$

where PDS is the proportion of area-wide net driving surface on expressways and A, B, C are unknown constants.

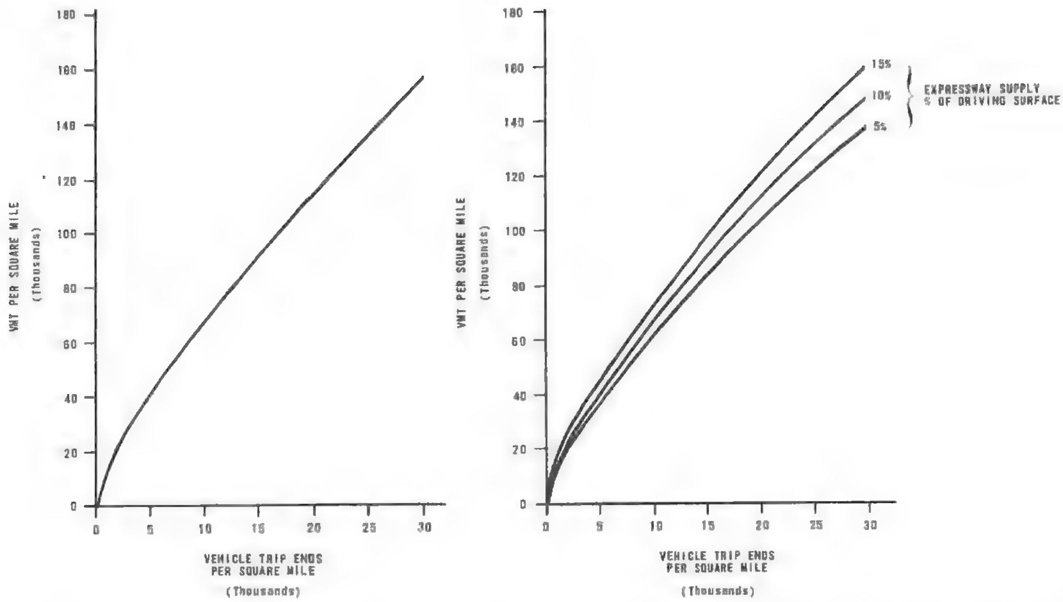

Figure 4. Projecting vehicle-miles of travel (a) as a function of vehicle trip ends and (b) as a function of vehicle trip ends and expressway supply.

Regression analysis was used to select values of A, B, and C that improved the ability to estimate vehicle-miles of travel and provided a reasonable level of response to changes in expressway supply.

The following equation was selected:

$$\text{VMT} = 64.3\ \text{VTE}^{0.74}\ e^{1.6\ \text{PDS}} \tag{5}$$

where VMT, VTE, and PDS are defined as before. The root mean square error is 0.91. The addition of the PDS term reduced the previously unexplained variation in VMT by 45 percent.

The ratio of vehicle-miles of travel to vehicle trip ends (VMT/VTE) decreases with increasing density and increases with increasing expressway supply as follows:

$$\frac{\text{VMT}}{\text{VTE}} = \frac{64.3\ e^{1.6\ \text{PDS}}}{\text{VTE}^{0.26}} \tag{6}$$

The decrease in this ratio with increasing density represents the discouragement to travel in high-density areas where travel costs are relatively high. The increase in the ratio with increases in expressway supply indicates the effect of providing a lower cost travel system as previously discussed. Both variations may be considered to include the effect of changes in the average length of trips with origin or destination in the area and as changes in the proportion and length of through trips in the area.

The distribution of travel on the different classes of roads is important in view of the differences in operating characteristics of the different classes of facilities. This distribution is determined by the relative supply of each type of facility measured by the relative driving surface and its ability to carry traffic (10).

The proportion of travel using expressways increases at a decreasing rate as the supply of expressways increases (Fig. 5). In the real range of operation, the redistribution effect is such that an increase in the supply of expressways leads to a decrease in the volume of travel on arterials and local streets. Consequently, an increase in the expressway supply will cause a decrease in average volume per lane on each class of facility.

The average speed of vehicles on each type of highway facility is determined by the design characteristics of the class of road and the delays caused by interference from other vehicles. The design characteristics determine the free speed. Delays resulting from friction between vehicles on the same roadway are related to the average volume per lane. Delays caused by entrances and exits and crossing movements of other vehicles are related to the density of automobile travel in the area, which can be measured by vehicle trip ends per square mile. The resulting speeds may be estimated by the following equations:

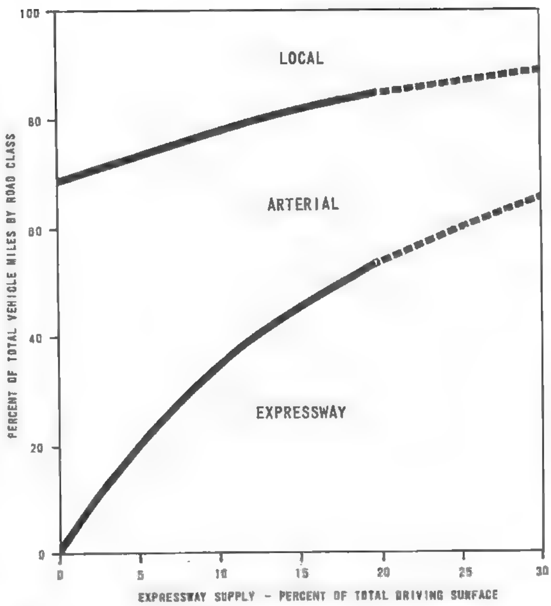

Figure 5. Effect of change in expressway supply on distribution of vehicle-miles of travel. Solid lines indicate the range of observed data (0 to 20 percent of road surface being expressways); dashed lines are extrapolated.

$$\text{SPD-EXP} = 55.3 - 0.73\ \text{VLE} - 5.19 \log \text{VTE} \tag{7a}$$

$$\text{SPD-ART} = 32.7 - 1.21\ \text{VLA} - 8.64 \log \text{VTE} \tag{7b}$$

$$\text{SPD-LOC} = 18.9 - 6.5 \log \text{VTE} \tag{7c}$$

where

SPD-EXP = average speed on expressways,
SPD-ART = average speed on arterials,
SPD-LOC = average speed on local streets,
VLE = average volume per lane on expressways in thousands,
VLA = average volume per lane on arterials in thousands, and
VTE = average vehicle trip ends per square mile in thousands.

The root mean square error is 0.81 for Eq. 7a and 0.93 for Eq. 7b.

Accident rates on each class of road are also related to the friction between vehicles and can be estimated from measures of vehicle trip-end density by the following equations:

$$\text{ACC-EXP} = 160.0 + 12.0\ \text{VTE} \tag{8a}$$

$$\text{ACC-AL} = 702.0 + 42.6\ \text{VTE} \tag{8b}$$

where

ACC-EXP = accident rate per 100 million vehicle-miles of travel on expressways,
ACC-AL = accident rate per 100 million vehicle-miles of travel on arterials and local streets, and

VTE = average vehicle trip ends per square mile in thousands.

The root mean square error in Eq. 8b is 0.69.

The expected changes in vehicle-miles of travel, distribution of travel between road classes, accident rates, and average vehicle speeds resulting from increases in the supply of expressways are shown in Figure 6. The extent to which capital expenditures should be incurred to obtain the potential highway user benefits indicated will be explored in the next section.

Determination of Highway Supply

The procedure used to determine the supply level that maximizes the objective function is shown in Figure 7. The input consists of the projected trip ends, population density, supply of arterial and local streets for the target year, and the existing supply of expressways (I). A proposed supply of expressways, which in the first instance is equal to the presently existing supply, is assumed (II). The travel description model is used to simulate future highway travel, providing estimates of vehicle-miles of travel, total travel time for private and commercial vehicles, total accidents on expressways and other roads, and all vehicle operating costs (III). The objective function is then evaluated (IV).

If this is the first estimation of the objective function for the given area (that is, if the proposed expressway supply is equal to that presently existing), an increase in expressway supply will automatically be considered (dotted line from IV to VII); otherwise this value of the objective function is compared to previously obtained values of

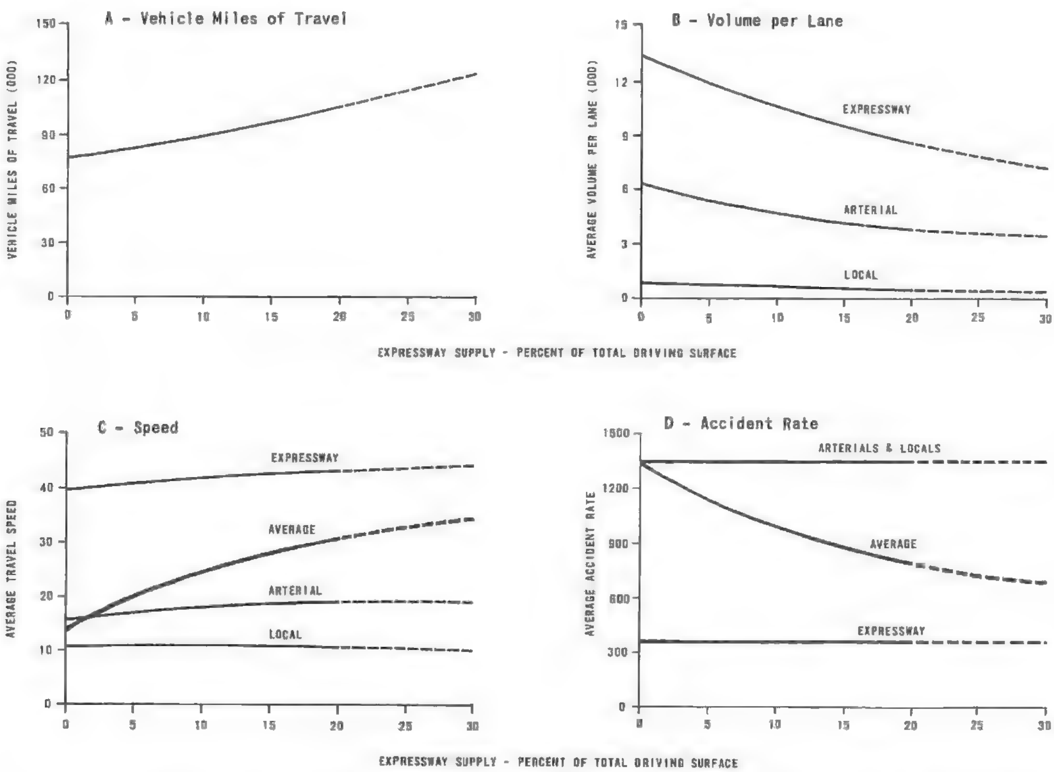

Figure 6. Effect of change in expressway supply on travel parameters for sample area with 15,000 vehicle trip ends per square mile. Solid lines indicate the range of observed data (0 to 20 percent of road surface being expressways); dashed lines are extrapolated.

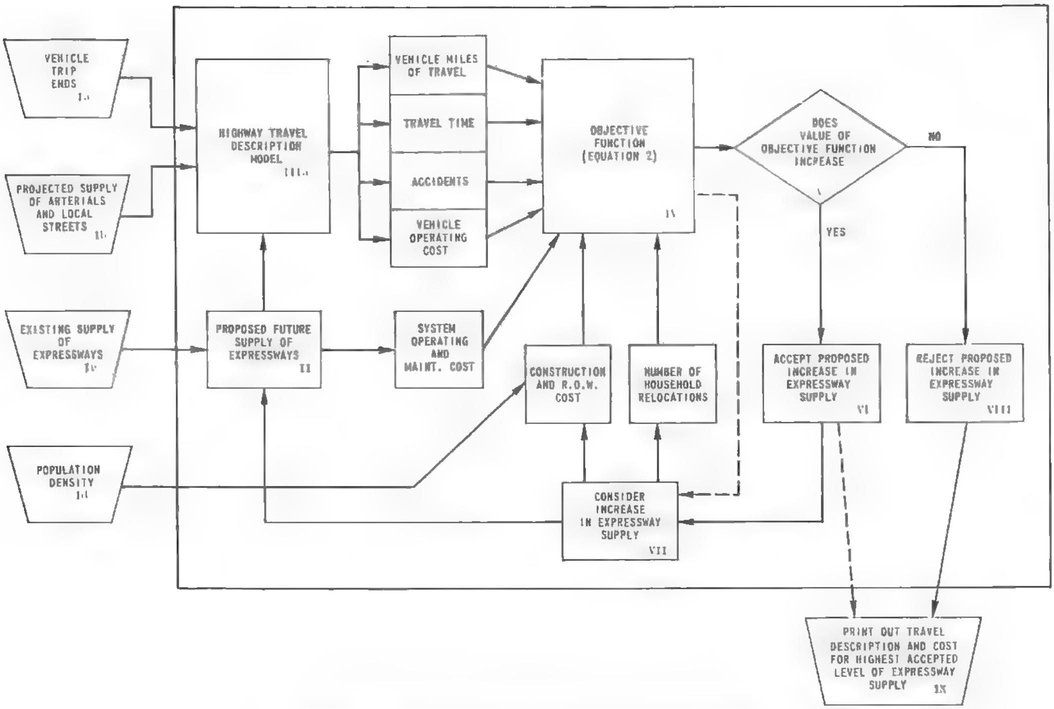

Figure 7. Model for highway needs determination.

the objective function at lower levels of expressway supply (V). If the value (i.e., the net benefit) has increased, the proposed future supply of expressways is accepted (VI) and a further increase in the expressway supply is proposed (VII). This process continues until the value of the objective function no longer increases with increases in the expressway supply, in which case the proposed increase in expressway supply is rejected (VIII). The resulting output (IX) is a description of travel cost and performance for the accepted level of expressway supply.

APPLICATION TO THE TRI-STATE REGION

The needs-determination program was applied to 83 analysis areas in the Tri-State Region. (The entire program required approximately 20 minutes operating time on the IBM 360/30. A FORTRAN program is available on request.) The output for each analysis area includes the recommended increase in expressway supply and the associated construction costs as well as estimates of future vehicle-miles of travel, distribution of travel between classes of facilities, average daily traffic volumes, average speed, and expected accidents.

The results of this analysis, summarized for the core area and three rings (Fig. 8), when compared to the previously published interim plan for the region indicated the need for a substantial increase in the proposed future expressway supply (Tables 1 and 2). Most of this increase in total needs is in the rapidly growing suburban portions of the region (Rings 1 and 2). This can be seen in the reduced average spacing between expressways, which represents the desired supply level, in the number of added route miles required, which makes allowance for existing facilities, and in the capital cost, which takes account of the variation in building costs in different portions of the region. The information obtained from this analysis is presently being used to guide the review and revision of the interim plan, which takes into consideration the network design factors and subjective evaluation of excluded social impacts.

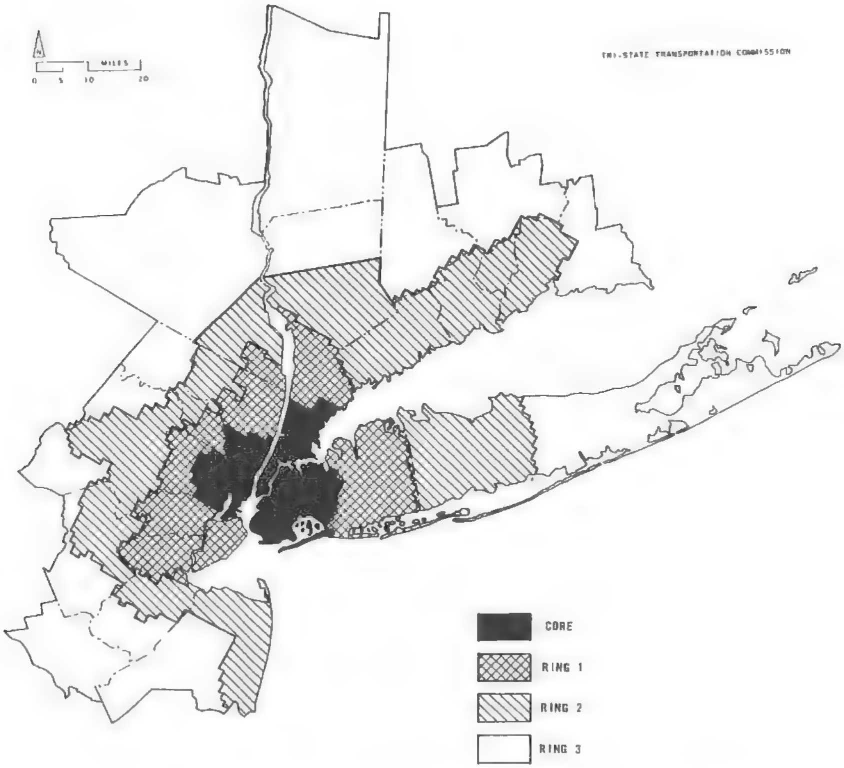

Figure 8. Data summary areas for highway needs in the Tri-State Region.

SENSITIVITY ANALYSIS

The weights assigned to the elements included in the objective function are subject to differences of opinion. Further, the assigned weights may vary over time and space. Sensitivity analysis can be used to indicate those elements for which the accuracy of the assigned weights is most important. The relative sensitivity of the results to variations in any of the objective weights has been estimated by considering the variation in average expressway spacing resulting from a variation of ± 10 percent in each of the objective weights (Table 3).

The cost of capital is the single most important factor in the list, with the value of time saved being much less sensitive but still quite significant. Study of both of these values should be emphasized in future research efforts. Variations of 10 percent in the remaining values cause only minor changes in the results obtained.

TABLE 1

HIGHWAY NEEDS EVALUATION PROGRAM

Area	Expressway Spacing		Added Expressways	
	1963	Proposed	Route Miles	Cost in Millions of Dollars
Core	3.1	1.9	190	2,200
Ring 1	7.4	2.4	550	3,650
Ring 2	15.7	4.1	820	3,770
Ring 3	32.8	11.2	520	1,740
Region	14.6	5.1	2,080	11,360

TABLE 2

HIGHWAY NEEDS INTERIM PLAN

Area	Expressway Spacing	Added Expressways	
		Route Miles	Cost in Millions of Dollars
Core	2.1	130	2,080
Ring 1	3.7	270	1,600
Ring 2	7.0	350	1,380
Ring 3	11.1	530	1,610
Region	6.8	1,280	6,670

TABLE 3

SENSITIVITY ANALYSIS FOR INFLUENCE OF OBJECTIVE FACTORS

Effect of 10 Percent Variation In	On Proposed Average Spacing Between Expressways[a] (percent)
Cost of capital	+11
Value of time saved	-7
Household relocation cost	+0.5
Accident costs	-0.3
Highway maintenance and operations	+0.2

[a]Average of change due to increase or decrease in factor weight. Sign indicates that change in result is in same direction (+) or opposite direction (-) as change in factor weight.

TABLE 4

SENSITIVITY ANALYSIS FOR SPEED ESTIMATES

Effect of 10 Percent Variation in Speed Estimated On	On Proposed Average Spacing Between Expressways[a] (percent)
Expressways	-6
Arterials	+9
Local streets	+6

[a]Average of change due to increase or decrease in speed estimate. Sign indicates that change in result is in same direction (+) or opposite direction (-) as change in speed estimate.

However, it is significant to note that the effect of completely ignoring community disruption as represented by the number of household relocations, which has actually been done in most studies, would be to overestimate the proposed expressway supply by more than 20 percent. This highlights the importance of considering such elements even if the exact weighting has not yet been established.

A similar approach was used to determine the relative significance of possible errors of some of the parameters used in the travel description model. Variations in the estimates of average vehicle speed, for all facility classes, turned out to be most critical (Table 4). This indicates the importance of improving our ability to predict future travel speeds.

FUTURE DEVELOPMENT OBJECTIVES

The work already completed in developing the method of needs evaluation described in this paper also indicates the need for additional work to broaden the potential application and improve the accuracy of needs estimates. Five specific areas of development are suggested:

1. Refinement of travel projections to include the feedback relationship between improved transportation facilities, land use, and future travel demands and the effect on highway travel of variations in the quality of transit service;
2. Refinement of the objective function based on improved valuations of the relative importance of individual objectives and consideration of the form of the equation to include the use of nonlinear relationships;
3. Exploration of the potential for, and importance of, incorporating additional social objectives in the objective function such as elimination of air pollution, reduction of traffic on local streets, and reduction of vehicle noise;
4. Refinement of technological relationships such as the equations used to estimate average travel speed and accident rates on different classes of facilities; and
5. Expansion of the model to include analysis of the supply of arterial as well as expressway facilities.

SUMMARY AND CONCLUSIONS

The needs estimation model described in this paper provides a useful method for evaluating highway needs in large metropolitan areas. The use of a consistent objective function provides a method for comparing the relative needs of disparate areas within a common region. The travel description model used provides reasonable estimates of future travel conditions sensitive to variations in the primary decision parameters. The approach described offers a simple method for obtaining approximate estimates of regional highway needs early in the transportation planning process at moderate cost in data collection and analysis. Further work will be directed toward refining the relationships used in order to obtain more reliable needs estimates in the future and toward expanding the scope of the model.

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DODOTRANS I: A Decision-Oriented Computer Language for Analysis of Multimode Transportation Systems

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•THIS PAPER summarizes the major features of a computer language and set of programs that have been under development at the Massachusetts Institute of Technology. There were two general objectives motivating this development, one substantive and one procedural: (a) the system should be policy-sensitive—that is, it should be able to predict the consequences of a wide range of alternative policies toward multimodal transportation systems in a theoretically acceptable manner; and (b) the system should support an analysis process in which the analyst explores a wide range of alternatives and amasses large quantities of information while seeking to develop his understanding of the policy issues in a particular problem. Elements of this general philosophy were reported in several early papers (1, 2, 3). The synthesis of these two general objectives was detailed more recently (4, 5).

The current system, Decision-Oriented Data Organizer-TRansportation ANalysis System (DODOTRANS), reflects this philosophy, elements of which were reported in earlier papers. DODOTRANS is policy-sensitive in that it analyzes multimodal transportation systems; can test a wide range of options; can predict a wide range of impacts; finds equilibrium of supply and demand in the network explicitly; and contains supply, demand, equilibrium, resource requirements, demand shift, and evaluation capabilities (although some are indeed very rudimentary).

DODOTRANS is designed to support an analysis process in that it has a command-structured problem-oriented language; stores data on secondary storage devices (disk) that can be addressed by names assigned by the user; logs the evolution of the analysis process to allow a wide variety of useful and interesting trade-offs; provides a flexible evaluation capability (6) and the "browsing" capabilities required for exploration of impacts among differenct groups (7); provides interface with mathematical optimization systems for use in searching for good alternatives; and is modular and expandable.

The implementation of this system has been gradual. The present version, DODOTRANS I, evolved out of several predecessor systems. The first was the M.I.T. Incremental Assignment Program, designed for experimentation with alternative traffic assignment procedures (8), developed by Martin for the IBM 7094 and the CTSS time-sharing system. The second step in this evolution was the development of TRANSET I, a subsystem of ICES, which is the Integrated Civil Engineering System (9, 10). TRANSET I is a problem-oriented language for traffic assignment, including incremental assignment and other procedures, and also a basic data base management system for transportation network analyses. TRANSET I and the later developments are all operational on the IBM System 360 series.

TRANSET I is the basic framework on which later developments have been achieved. TRANSET II (5, 11) extended TRANSET I to include additional capabilities for the analysis of multimodal networks, with a variety of policy options to be tested and impacts to be predicted. DODO (12) extended an early version of TRANSET II to include an elementary decision-oriented data structure, as hypothesized in the problem-solving process (PSP) model (2).

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DODO and TRANSET II have been combined, and significant new capabilities have been added to create DODOTRANS I (13, 14). This system includes the multimodal analysis models of TRANSET II, the PSP capabilities of DODO, and new demand models, greatly expanded technology models, and evaluation capabilities (15). These capabilities are detailed in the following section.

DODOTRANS is still an evolving system. At any time, there is one version of the system that is "frozen" in development and maintained in operational status for classroom, research, and field use. At the same time, several additional versions are serving as "test beds" for development of new capabilities and for experimental use by students and research staff. We see the DODOTRANS system as a "breadboard" on which we can experiment with new approaches to the analysis of transport systems.

CURRENT DODOTRANS CAPABILITIES

There are two sets of theoretical concepts underlying DODOTRANS. One is the equilibrium approach to transportation systems analysis (4), which is briefly summarized here. DODOTRANS represents one set of approximations to the equilibrium approach that makes it operationally feasible for application to substantive transportation problems. The other is the PSP model (4), which will not be reviewed here.

The transportation systems analysis problem can be expressed concisely in terms of the following variables, each of which is a collection of many data items:

T = specification of the transportation system in terms of the full set of available options—technologies, networks, vehicles, and operating policies;
A = specification of the activity system in terms of both exogenous characteristics, such as national population and economic trends, and controllable options, such as land use controls;
F = pattern of flows of passengers or freight, or both, in the transportation system;
L = service characteristics of a particular flow or set of flows—travel times, fares, comfort, and the like; and
V = volume of flows on the transportation network.

These variables can be used to specifiy supply functions S, which give the level of service as a function of the transportation options and the volume of flows, and demand functions D, which give the volume of flows as a function of the activity system options and the level of service:

$$L = S(T, V)$$

$$V = D(A, L)$$

The intersection of S and D within the constraints of T results in an equilibrium pattern of flows in the system, F, characterized by specific values of flows, V_1, and the levels of service, L:

$$F = (V, L)$$

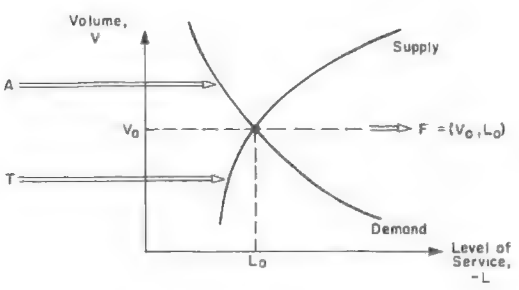


Figure 1. The equilibrium approach applied to transportation systems analysis.

These relationships are shown graphically in Figure 1.

There are many difficulties inherent in translating this conceptual framework to an operational transportation systems analysis procedure. A number of approximations to this framework must be made to implement an operational procedure. DODOTRANS represents one such set of approximations.

In terms of this theoretical concept discussed in the foregoing, DODOTRANS provides the capability of analyzing

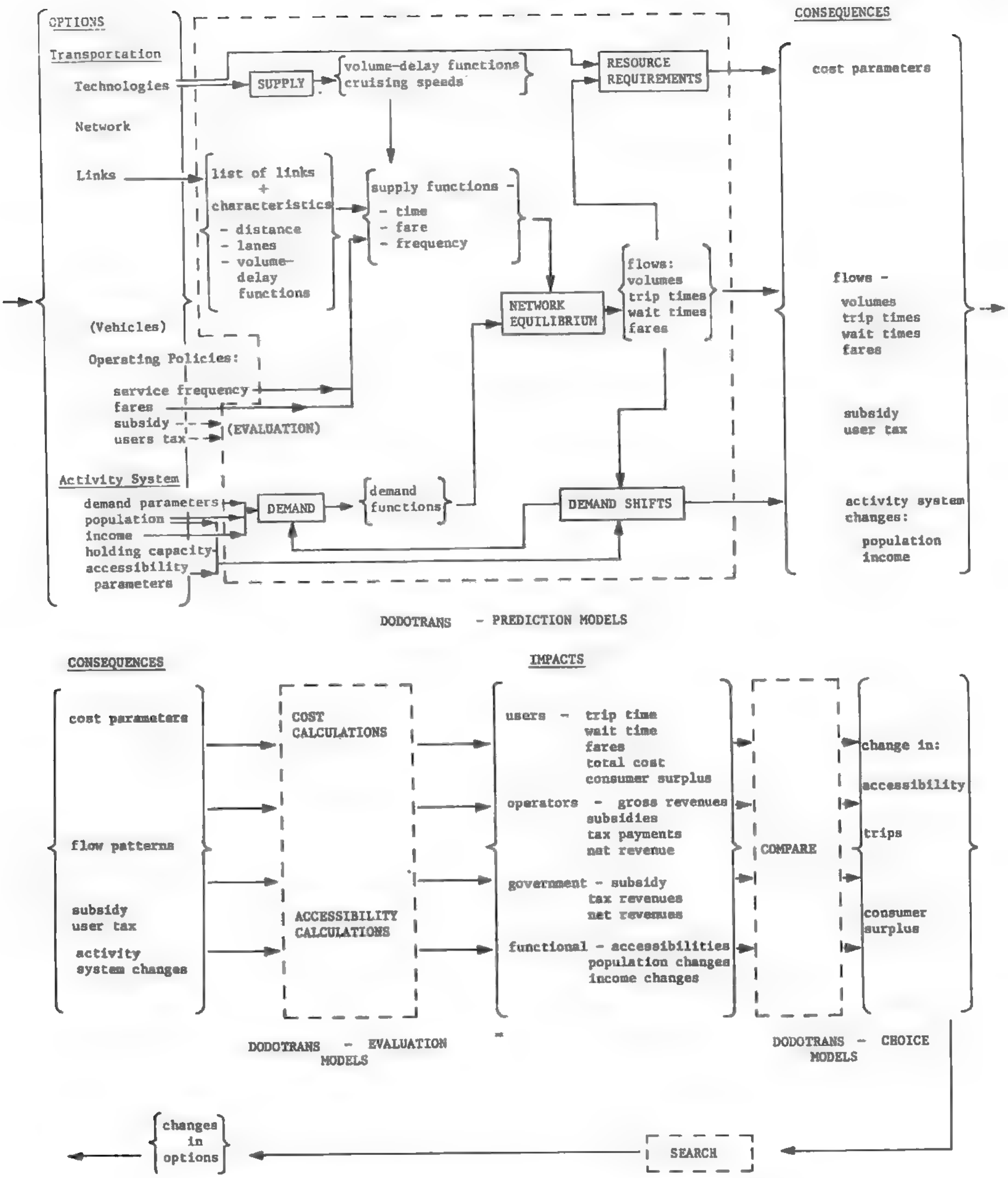


Figure 2. DODOTRANS and relation to equilibrium structure.

transportation problems by predicting supply and demand equilibrium in a multimodal transportation network. Because the nature of the transportation systems analysis problems can be described in terms of options, impacts, and the basic structure of the set of prediction models (5), it is useful to describe the capabilities of DODOTRANS in these same terms. Figure 2 shows the structure that underlies these capabilities.

Options

The basic options and the corresponding elements of DODOTRANS are as follows, when the simplest cost model is used:

1. Technologies—Options include volume-travel time functions, where each function gives travel time in minutes per mile per lane and as a function of volume in passengers per day (up to 14 volume-delay functions can be specified), and cost structure, where for each mode the fixed cost is in dollars per year and variable cost is in dollars per passenger mile.
2. Multimodal Network—Network options are specified by listing, for each link, its origin and destination node.
3. Links—Options for each link in the network include its length in miles, the number of lanes, and the volume-delay function.
4. Vehicles—There are no explicit specifications of vehicles.
5. Operating Policies—Options include frequency of service for each mode and pair of origin-destination districts in departures per day, fare for each mode and pair of origin-destination districts in cost per passenger, subsidy for each mode with total subsidy in dollars per year, and user tax for each mode as a percentage of the fare.
6. Activity System—Options include base year total population, per capita income, and population holding capacity for each district, and travel demand parameters as appropriate for each demand model.

When the single route cost model is used, the following basic options can be specified (16):

1. Technologies—Options include total route loading, unloading, and delay times; average route speed; and cost structure (labor, maintenance, and overhead costs associated with fixed facilities can be specified as fixed costs and in terms of units of capacity, actual volume, vehicle distance, and vehicle-hours).
2. Route Description—Options include actual volume, capacity, route distance, existing fixed facilities, and construction costs of fixed facilities.
3. Vehicles—Options include physical characteristics (payload, average load factor, and utilization rate) and cost structure (labor, maintenance, overhead, and fuel costs associated with vehicles can be specified in terms of units of capacity, actual volume, vehicle distance, and vehicle-hours).

When the network cost model is used, the following basic options, in addition to those listed under the first set of options, can be specified:

1. Links—Options include, for each link of the network, its fixed cost per year and its maintenance cost for a unit of capacity.
2. Vehicles—Options include physical characteristics (load factor, payload, utilization rate, parameters for estimating labor, maintenance, and fuel requirements) and cost structure (unit vehicle acquisition, labor, and fuel costs, and passenger service costs).
3. Operating Policies—Options include subsidies and taxes as lump sums by mode and based on vehicle use, link capacities, and number of passengers; and user tolls by route.

Impacts

The predicted impacts are grouped as follows:

1. Users—Impacts include total volume of passengers served by mode, by origin, and by destination; total trip time by mode, by origin, and by destination; wait time by mode, by origin, and by destination; and fare paid by mode, by origin, and by destination.
2. Operators—Impacts include total operating and governmental cost by route and by mode; gross revenue by mode, and by origin district; and net revenue by mode.
3. Government—Impacts include total subsidy by route and by mode, total user tax revenue by route and by mode, and net revenue by mode.
4. Physical—There are no physical impacts.
5. Functional—Impacts include accessibility by origin district and by mode; and population and income change by district.

Consequences

To determine these impacts, the following consequences must be predicted by the network equilibrium analysis:

1. Flow Volumes—Consequences include interzonal flow volumes (passenger trips) by mode, by origin, and by destination; and link flow volumes (total passenger flow for each link).
2. Levels of Service—Consequences include interzonal trip times by mode, by origin, and by destination; interzonal wait times by mode, by origin, and by destination (a fraction of the inverse of frequency of service, which is specified as input); interzonal total travel times (wait times plus trip times) by mode, by origin, and by destination; link speeds and travel times; and interzonal fares by mode, by origin, and by destination (specified as input).
3. Resource Requirements—Consequences include total fixed plus variable cost by mode, total user tax revenues by mode, and total government subsidy by mode.
4. Activity System Changes—Consequences include accessibility by mode and by district; and change in population and per capita income by district.

Prediction Models

The consequences described are predicted from the options using the prediction models briefly described in this section.

Demand Models—There are four basic demand model capabilities. One is specific, the other three are very general forms. The specific model is an early version of the Baumol-Quandt abstract mode model (17).

Conductivity demand models—The first general demand model form has been termed a conductivity model because it contains separate terms describing the ease of travel between origin and destination by each mode. The conductivity terms for competing modes are summed to provide a determinant of trips by all modes between an origin-destination pair. Also, the ratio of conductivity by one mode to the sum of conductivities by all modes is the mode split fraction for the given mode. In addition to the conductivity terms, the model includes a set of mode-independent terms. The mathematical form of the model is as follows:

1. Conductivity terms:

$$C_{kij} = a_k \prod_{\text{variables } l} V_{kijl}^{b_{kl}}$$

2. Mode-independent terms:

$$K_{ij} = \prod_{\text{variables } l} O_{il}^{d_l} \prod_{\text{variables } l} D_{jl}^{e_l} \prod_{\text{variables } l} W_{ijl}^{f_l}$$

3. Total trips:

$$TT_{ij} = K_{ij} \sum_{\text{modes } l} [C_{lij}]^g$$

4. Trips by mode:

$$T_{kij} = \frac{TT_{ij} C_{kij}}{\sum_{\text{modes } l} C_{lij}}$$

where

a_k = a mode-specific conductivity parameter;
b_{kl} = a mode-specific parameter associated with variable V_{kijl};
c and g = mode-independent general parameters;
d_l, d_l, f_l = mode-independent parameters associated with variables O_{il}, D_{jl}, and W_{ijl} respectively;
V_{kijl} = the l th variable describing a travel "price" between origin i and destination j by mode k;
O_{il} = the l th variable describing trip-generating characteristics of origin i;
D_{jl} = the l th variable describing trip-attracting characteristics of destination j;
W_{ijl} = the l th variable describing a mode-independent travel "price" between origin i and destination j;
C_{kij} = the conductivity for travel from i to j by mode k;
K_{ij} = the mode-independent determinant of travel from i to j;
TT_{ij} = the trip total, by all modes, from i to j; and
T_{kij} = the number of trips from i to j by mode k.

As implemented in DODOTRANS, the following variables are used:

1. For V_{kijl},

$$V_{kij1} = t_{kij}, \text{ travel time in minutes}$$

$$V_{kij2} = C_{kij}, \text{ fare in dollars}$$

$$V_{kij3} = (1 - e^{-hf_{kij}})$$

where h is a constant and f_{kij} is the frequency in departures per day.

2. For O_{il},

$$O_{i1} = P_i, \text{ the population in millions}$$

$$O_{i2} = Y_i, \text{ the average per capita income in dollars}$$

3. For D_{jl}, P_j and Y_j are as in 2.
4. For W_{ijl},

$$W_{ij1} = t_{bij}, \text{ the fastest travel time in minutes}$$

$$W_{ij2} = c_{bij}, \text{ the cheapest fare in dollars}$$

$$W_{ij3} = f_{bij}, \text{ the largest frequency in departures per day}$$

The conductivity model has, as two special cases, the McLynn model being used by the Northeast Corridor Transportation Study (18), and the Baumol-Quandt model as formulated for the prototype analysis (11). These special cases occur when the parameters have the following settings:

1. For the McLynn model, all f_l parameters equal zero.
2. For the Baumol-Quandt model, (a) all a_k parameters and the g parameter equal one; (b) all b_{kl} parameters would be the same for each mode k; and (c) the f_l parameters should be obtained from the "best" and "ratio" price parameters (indicated in the following by the b and r subscripts) normally associated with the Baumol-Quandt model as follows:

$$\text{time price—}f_1 = a_{t_b} - a_{t_r}$$
$$\text{fare price—}f_2 = a_{c_b} - a_{c_r}$$
$$\text{frequency price—}f_3 = a_{f_b} - a_{f_r}$$

Modal competition product form model—The second general model form has been termed a modal competition model because a set of parameters is provided that relates trips by one mode to "price" variables for competing modes. Another characteristic of the model is that variables in the model are combined using a single operator, multiplication.

The mathematical form of the model is

$$t_{kij} = a_k \prod_{\text{variables } l} O_{il}^{b_{kl}} \prod_{\text{variables } l} D_{jl}^{c_{kl}} \prod_{(\text{modes } m)} \prod_{(\text{variables } l)} V_{mijl}^{d_{kml}}$$

where

a_k = a mode-specific general parameter,
b_{kl} and c_{kl} = mode-specific parameters associated with variables O_{il} and D_{jl},
d_{kml} = a doubly mode-specific parameter associated with variable V_{mijl} (it indicates how trip-making by mode k will change due to changes in travel "prices", ℓ, for mode m), and
O_{il}, D_{jl}, and V_{mijl} = variables with the same definitions as for the conductivity model.

As implemented in DODOTRANS, the variables used for O_{il}, D_{jl}, and V_{mijl} are the same as for the conductivity model. The product form of the modal competition model has the same characteristics as the Kraft-SARC demand model (19).

Modal competition summation form model—The third general demand model differs from the modal competition product form only in that the model terms are summed rather than multiplied together. The mathematical form of the model is

$$T_{kij} = a_k + \sum_{\text{variables } l} b_{kl} O_{il} + \sum_{\text{variables } l} c_{kl} D_{jl} + \sum_{(\text{modes } m)} \sum_{(\text{variables } l)} d_{kml} V_{mijl}$$

where the variables and parameters have the same definition as for the product form model.

As implemented in DODOTRANS, the variables used for O_{il}, D_{jl}, and V_{mijl} are the same as for the conductivity model. The summation form of the modal competition model has a simple structure useful for teaching purposes.

Supply and Resource Requirements Models—There are three basic capabilities. In one formulation the supply models are external to the computer programs. Hand calculations and engineering judgment are used to develop the basic functions required: cost coefficients for each mode, volume-delay functions, and cruising speed estimates. These are then input explicitly to DODOTRANS as data.

A second model handles a wide variety of cost components (16) and is very useful for parametric exploration. However, at present it is restricted to a single link at a time. The input is a number of variables describing the costs and required amounts of direct labor, maintenance, overhead, and fuel; the costs of vehicles and fixed facilities (supporting way and stations or terminals); the characteristics of the route; the design capacity and expected traffic volume; and the required amount of fixed facilities. From these variables the desired cost is computed.

This model treats a number of measures of the cost of a transportation system. Each of these is figured in units of dollars per year. The most obvious measure is total cost, that is, total yearly operating costs plus the yearly payment on investment. From this, two averages can be computed. The first of these is based on the capacity of the system; that is, average cost equals total cost divided by capacity in passengers per year or tons per year. The second average is based on actual volume: average cost equals total cost divided by actual volume in passengers per year or tons per year.

Another cost is one that is used a great deal in economic analysis, marginal cost. As used by the model, the marginal cost is the change in total cost for one additional unit of capacity or, in other words, the cost of that additional unit of capacity.

Corresponding to these four costs, four others take into account only the cost of investment in fixed facilities: total investment cost, average investment cost based on capacity, average investment cost based on actual volume, and marginal investment cost. In the calculation of these costs, operating costs are ignored and only investment costs are considered.

The model computes costs based on the number of passengers or tons of freight carried over a route. Of course, the number of passengers or the amount of freight carried will vary along the route, but there are two ways that this problem can be handled. The first method is to use an average number of passengers or amount of freight over the route. The second is to treat each link of the route separately. The latter method requires more computation but does not require an average payload figure and provides more detailed information.

A third model has a less flexible cost structure, but is capable of operating over an entire network. Resources consumed and corresponding costs are predicted, as well as minimum fleet size required.

The differences between the second and third models are as follows:

1. The second model only deals with one route, a single link over which one vehicle type of one mode may travel. The model must be iterated externally to handle more than one link, route, vehicle type, or mode. This model handles a large number of links, routes, vehicle types, and modes automatically. Each mode of the origin-destination combination generated in DODOTRANS becomes a route to be analyzed in the model. For each route, a vehicle type is specified. A number of parameters and costs may be specified by vehicle type. Also, each route is composed of a number of links, each of which may be described by a number of parameters and costs.

2. Vehicle requirements are determined to meet predicted demand, or a prespecified frequency of service, whichever requirement is greater. In the second model, frequency is not relevant; vehicle requirements are determined to utilize fully the available route capacity or to meet the specific demand.

3. A number of output measures are provided so that available empirical data on cost and on the constants used to calculate resource coefficients can be used with little adjustment.

4. The effects of governmental actions, in terms of taxes and subsidies collected from transportation operators, may be considered using the model. Operator costs due to taxes and subsidies are kept separate from costs due to technologies, but they are included in the model.

Network Equilibrium—The approach for computing equilibrium flows in the multimodal network is an incremental-loading traffic assignment procedure with variable increment, which is consistent with the demand model used.

Demand Shifts—An extremely simple model for computing the distribution of population and income is provided. The growth of each district in the region is computed as a weighted function of accessibility, present population, holding capacity, and an exogenously specified regional growth rate.

Evaluation

The impacts on the various groups are determined from the predicted consequences. In order to evaluate alternative systems, it is necessary to aggregate these consequences to produce various overall measures of the impacts of each alternative. The following evaluation "models" are, with the exception of accessibility and consumer surplus, simple summations over zones or modes, or both. (Accessibility and consumer surplus are computed consistent with the demand model used.) That is, where aggregate measures of impact are constructed, each group is weighted equally; e.g., all modes, origins, and or destinations are weighted equally when passenger hours or total fares or revenues are summed to various aggregate levels. Some of these measures

are directly specified as input (e.g., subsidy); others are functions of the predicted flow patterns.

1. Users—Measures include (a) total trip time by mode, by origin; by mode; system total; (b) total wait time by mode, by origin; by mode; system total; (c) average travel time by mode, by origin; by mode; system total; (d) average fare by mode, by origin; by mode; system total; and (e) user total cost—for specified utilities (relative weights of trip time, wait time, and fare) a weighted total cost is computed and aggregated by mode, by origin; by mode; system total.
2. Operators—Measures include (a) gross revenue from user fares by mode, by origin; by mode; system total; (b) gross revenue from government subsidy by mode; system total; (c) gross payment to government via user tax by mode; system total; and (d) net revenue by mode; system total.
3. Government—Measures include (a) subsidy to operators by mode; system total; (b) user tax revenues from operators by mode; system total; and (c) net revenue by mode; system total.
4. Functional—Measures include (a) accessibilities by origin, by mode; by origin; by mode; system total; (b) population change by zone; and (c) income change by zone.

These component and aggregated measures can be used in evaluating such comprehensive objectives as regional growth pattern, income distribution, fiscal feasibility, and political feasibility.

A flexible evaluation capability is provided that builds on the PSP structure. The basic procedures outlined in the PSP model and implemented in DODOTRANS are given in the following:

1. Generate alternative actions for solving the problem.
2. Predict the consequences of each action with the aid of a set of predictive models—the equilibrium model and related models.
3. Evaluate the consequences (impacts) of each action by using an evaluation model that transforms predicted consequences into normative goal performance terms or valuations.
4. Generate a preference ordering of the actions based on their relative goal performance.
5. Examine the best action as indicated by the preference ordering. If it satisfies all of the constraints of the original problem, or if resources for the analysis have been exhausted, implement it in the real world. Otherwise, search for new alternative actions and repeat the process.

The evaluation model in DODOTRANS is based on the concept of a goal fabric (6). A goal fabric is a set of goal variables that are defined in terms of arithmetic operations performed on basic consequences. The basic consequences are the outputs from the predictive models, e.g., fare, frequency of service, travel time, and trips, each of which may have different values for each route in the system. A route is defined by specifying an origin, destination, and mode. Examples of goal variables in the DODOTRANS system are maximum fare, average frequency of service, minimum travel time, and product of fares and trips. These illustrate the operations "maximum", "average", "minimum", and "product".

The user can define, and give names to, a number of goal fabrics. He can then evaluate the consequences of a particular action by computing the values of the goal variables in any goal fabric. Each goal variable can be computed over a number of ranges of evaluation. A range of evaluation consists of a set of one or more combinations of origins, destinations, and modes (for example, average travel time from Hartford to New York by air and by all modes; and from Hartford to all zones by air and by all modes).

The DODOTRANS user can also compare several actions by comparing the values of a particular goal variable for each of the actions. The actions are automatically ranked according to these values, and the minimum, maximum, and absolute and percentage differences are displayed.

To assist in evaluation, relevant consequences can be displayed graphically on plotter or scope by means of such commands as PLOT NETWORK, DISPLAY LINK VOLUMES, TRAVEL TIMES, SPEEDS. Several alternatives can be compared, to evaluate the differences between them, with such commands as

1. COMPARE TRIPS, for a summary of the differences between the two flow patterns;
2. COMPARE SURPLUSES, for comparison of user benefits as measured by consumer surplus; and
3. COMPARE ACCESSIBILITIES, for functional impacts.

Search

Two basic types of search capabilities are provided. A transportation system alternative can be generated explicitly by the user supplying the data or by calling a mathematical optimization formulation.

Generating an Alternative Explicitly—To generate an alternative explicitly, the following commands can be used.

1. Transportation options: (a) READ NETWORK, for general network characteristics; (b) LINKS, for network connectivity and link characteristics; (c) READ VOLUME DELAY SETS, for generalized supply functions; and (d) READ MODAL SERVICE DATA, for interzonal fares and frequencies and cost parameters for each mode.
2. Activity system options: (a) READ ACTIVITY, for populations, incomes, and holding capacities for each district; and (b) PARAMETERS, for demand model parameters.

In addition to specifying a completely new alternative, it is also possible to generate an alternative by using portions of another alternative previously stored in the computer:

3. STORE, to save a network, volume-delay set, modal service data, or activity pattern for an alternative on secondary storage as a permanent file for future reference.
4. To create a new alternative by modifying one previously stored on secondary storage: (a) MODIFY NETWORK, name of network is changed; ADD LINK, DELETE LINK, CHANGE LINK, specification of changes; (b) MODIFY MODAL DATA, name of data to be changed; MODE COST, MODE FREQUENCY, specification of changes; (c) READ ACTIVITY, name of data to be changed; DISTRICT, specification of changes.

Use of Mathematical Optimization—A communications system has been developed that allows the DODOTRANS user to set up an optimization formulation of his transportation search problem with a minimum of information describing the problem. After the formulation is set up, it may be executed using existing optimization packages, and the results are returned to DODOTRANS for output and, possibly, data modification.

Time-Staging of Network Improvements in the Face of Uncertainty—Uncertainty is an essential aspect of transportation planning. There will always be uncertainty as to demand, as to the characteristics of transportation technology, and as to the values, public and private, to be used in reaching a decision. This uncertainty must be recognized, and techniques for treating uncertainty explicitly must be an integral part of analysis of transportation systems (20).

One method for handling uncertainty uses the general techniques of decision theory (SDT) (21, 22). An early application of SDT to transportation problems was in the process of highway location (23). Later applications included pavement design (24) and traffic engineering problems (25).

The need to apply SDT to transportation planning per se was described in a recent survey report (5) where work then in progress was reported. More recently, Hutchinson (26) has outlined, in a simple example, the application of SDT to planning a rail demonstration project. The use of SDT in transportation planning is promising.

Significant advances in techniques are required to exploit the full potential of SDT. Since 1966, work has been under way at M.I.T. to develop such techniques. Johnson (27) has applied the Bayesian decision theory approach to the problem of determining how much information to collect in transportation planning. Jarmillo (28) explored alternative formulations of demand models suitable for Bayesian reference in the SDT framework. In work nearing completion, Pecknold (29) is developing practical computational techniques for applying SDT to realistic transportation problems.

While these efforts to develop specific techniques have been proceeding, it has been our long-term objective to integrate these results into our system of computer programs

for transportation analysis. To this end, preliminary capabilities have been incorporated into DODOTRANS for exploring the time-sharing of alternatives in the face of uncertainty.

Other Developments—Experiments are being conducted with a variety of other search techniques. As these are developed and tested, they will be incorporated into DODOTRANS. Of particular note are specific heuristic search techniques.

AN EXAMPLE OF THE USE OF DODOTRANS I

An example of the use of DODOTRANS I to perform transportation systems analysis is discussed in this section. This example is only meant to illustrate the DODOTRANS capabilities and commands, and therefore has little real-world significance. DODOTRANS has been used to analyze a real region, the Northeast Corridor, in a prototype analysis reported elsewhere (11), and is currently being used to analyze other prototype problems, including an urban transit corridor and an "airport access" problem.

Options

In order to demonstrate most of the major DODOTRANS commands, a hypothetical problem has been formulated. The analysis area, shown in Figure 3, consists of three districts in which intercity air and rail passenger travel is to be analyzed.

In order to keep the network simple, it is assumed that all intercity passengers in the three districts begin and end their trips in the district center, which is the location of the rail station. This assumption eliminates links representing travel to each air and rail station from scattered locations within the district. These could be added if desired.

A set of options representing an existing situation are illustrated in Figure 4 and Tables 1 and 2. The air mode has the lower fixed costs. The rail mode has the lower variable costs. Volume/time functions for air access roads and airports increase as volumes increase, reflecting possible congestion for air travelers until they become airborne. Rail line capacities are also limited, but rail station delays are constant, independent of volume.

Separate networks are developed, each reflecting the unique structure of access, terminal, and line-haul links for a particular mode. Governmental and operators'

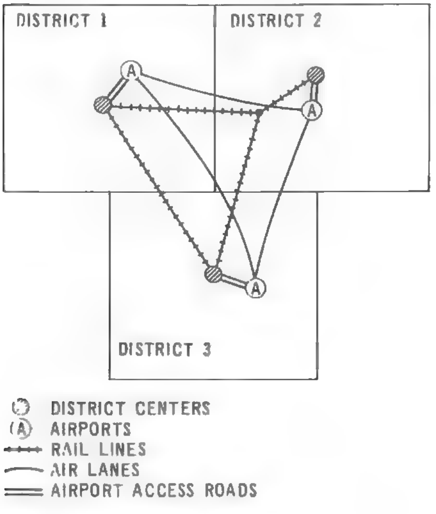


Figure 3. The analysis area.

TABLE 1

THE ACTIVITY SYSTEM: DISTRICT DATA

District	Population (in thousands)	Per Capita Income (dollars per year)	Holding Capacity (in thousands)
1	4,000	2,000	8,000
2	2,700	2,200	4,500
3	3,600	1,900	10,000

TABLE 2

THE ACTIVITY SYSTEM: DEMAND MODEL PARAMETERS

Constant	4.5×10^4
Exponents	
Origin population	0.5
Destination population	0.5
Origin income	0.5
Destination income	0.5
Fastest time	-2.09
Time ratio	-2.18
Lowest fare	-0.955
Fare ratio	-2.24
Most frequent	0.0
Frequency ratio	0.44

a. The technologies: Costs

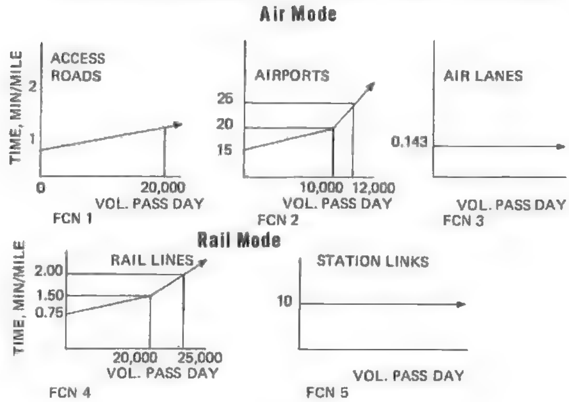
Air Mode

Fixed cost	$1.5 million per year
Variable cost	$0.05 per passenger-mile

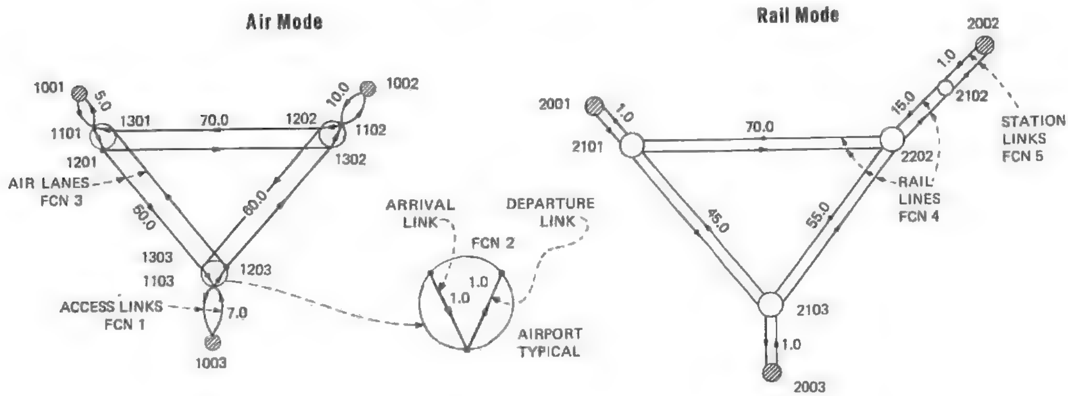
Rail Mode

Fixed cost	$5 million per year
Variable cost	$0.02 per passenger-mile

b. The technologies: Volume/Time Functions



c. The network



d. Operating policies

Air Mode

Subsidy = $500,000 per year; user tax = 5 percent of fare.

FREQUENCIES (departures per day)				FARES (dollars per trip)			
From District	To District 1	2	3	From District	To District 1	2	3
1	–	15	11	1	–	17	15
2	15	–	18	2	17	–	16
3	11	18	–	3	15	16	–

Rail Mode

Subsidy = $10,000 per year; user tax = 0

FREQUENCIES (departures per day)				FARES (dollars per trip)			
From District	To District 1	2	3	From District	To District 1	2	3
1	–	25	17	1	–	6.25	4.25
2	25	–	30	2	6.25	–	5.50
3	17	30	–	3	4.25	5.50	–

Figure 4. The options.

policies are specified for each mode in terms of subsidies, tax rates, and interdistrict fares and frequencies. The activity system is described as district data and demand model parameters (Tables 1 and 2).

Runs for the Existing Alternative

DODOTRANS commands describing the options shown in the figures were developed, and the prediction models were used to generate existing consequences and impacts.

The results of the computer runs for the existing data are given in the Appendix in runs 1 through 4, where both the input commands and the outputs are listed. These runs indicate that a total of 26,840 trips are made each day, 3,138 by air and 23,702 by rail. The average travel time for all trips is 72 minutes, and the average user cost is $10.11. Total yearly operator's profit is $12.0 million for the air mode and $27.1 million for the rail mode. Net annual government revenue is $0.4 million. These numbers are only some of the more aggregate measures determined by DODOTRANS. Many other useful numbers are provided in the output.

Proposed Changes

After establishing the "base case", proposed transportation changes can be evaluated. The following changes to the existing data were proposed for this example:

1. Construct a new direct rail link between districts 1 and 2, with a distance of 80 miles.
2. Improve airport design and procedures to reduce terminal delays to half of their original levels.
3. Double existing rail frequencies between districts 1 and 2 to 50 trains per day.
4. Reduce existing rail fares between districts 1 and 2 by $1.00 to $5.25 per trip.
5. Increase the average per capita income of district 2 residents by $100 to $2,300 per year.

All of these changes can be made simply by using DODOTRANS to modify the original data, which have been saved in named secondary storage files. These modifications create a new network and new district and modal data sets.

Runs for Proposed Alternative

The DODOTRANS commands that perform the modifications described in the preceding and then continue to predict new consequences and impacts are shown in runs 5 through 7. After the prediction and output phases are completed for the proposed alternatives, the DODOTRANS alternative comparison commands are used to compare the existing and proposed alternatives. Also, the change in accessibilities between the two alternatives is used to predict new populations and incomes.

Highlights of the alternative comparisons are that total trips have increased by 5,416, which is 20 percent higher than the base consequence. Air trips have increased 71 percent to 2,240, and rail trips have increased 13 percent to 3,176. The total change in consumer surplus per day, however, is -$7,209, thus indicating that in total the travelers are worse off after the proposed changes are made. Going back to less aggregated results, total consumer surpluses due to changes in travel times and waiting times are positive but are outweighed by a large decrease in consumer surplus resulting from changes in user fares.

The population predictions indicate that district 2 will grow slower than the other districts. The income predictions indicate that district 3 will have the smallest increase in income levels.

CONCLUSIONS

We want to stress the evolutionary nature of DODOTRANS. It is a "breadboard" on which we experiment with new models and approaches. As these are tested out, they are incorporated into the current operational version of the system.

DODOTRANS is an experimental system. We use it actively in our own teaching and research and are applying it to real problems. We are especially anxious to get critical evaluation of this system, suggestions for further development, and tests of its capabilities in real problems. Although the system has not been released for wide distribution, we would like to try to collaborate with anyone who would like to experiment with use of the system.

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Appendix

COMPUTER PRINTOUT DATA

```
READ NETWORK 'EXAMPLE' ZONES 6 VOL/DELAY SET 'EXAMPLE'

NETWORK EXAMPLE       INPUT NODES=        0     LINKS=        0

$   LINKS FRCM ZCNES FIRST

LINK 1 FROM 1001 TO 1101 DISTANCE 5 LANES 1 VOL/DELAY 1

LINK 2 1002 11C2 10 1 1, 1003 1103 7 1 1

LINK 3 2001 2101 1 1 5, 2002 2102 1 1 5, 2003 2103 1 1 5

$   AIR ACCESS LINKS

LINK 4 1101 1C01 5 1 1, 1102 1002 10  1 1, 1103 1003 7 1 1

$   NOW AIRPORT LINKS

LINK 5 1101 1201 1 1 2, 1301 1101 1 1 2

LINK 6 1102 1202 1 1 2, 1302 1102 1 1 2

LINK 7 1103 1203 1 1 2, 1303 1103 1 1 2

$   NOW AIR LANE LINKS

LINK 8 1201 13C2 70 1 3, 1201 13C3 50 1 3

LINK 9 1202 1301 70  1 3, 1202 1303 60 1 3

LINK 9 1203 1301 50 1 3 , 1203 1302 60 1 3

$   RAIL LINKS - START WITH STATIONS

LINK 11 2101 2001 1 1 5, 2102 2002 1 1 5, 2103 2003 1 1 5
```

```
$   LINE HAUL RAIL LINKS

LINK 12 2101 2202 70 1 4, 2202 2101 70 1 4

LINK 13 2101 2103 45 1 4 , 2103 2101 45 1 4

LINK 14 2102 2202 15 1 4 , 2202 2102 15 1 4

LINK 16 2202 2103 55 1 4, 2103 2202 55 1 4

$   DUMMY LINKS

LINK 16 1001 2001 160 1 6, 2001 1001 160 1 6

EDIT NETWORK

NETWORK EXAMPLE  HAS BEEN READ

STORE NETWORK

NETWORK EXAMPLE  HAS BEEN STORED ON DISK.




$  RUN 1

DODOTRANS

READ VOL/DELAY SET 'EXAMPLE' FUNCTIONS 6 POINTS 3

  V/D 1 LOCAL 2 C 1 20000 2 40000 3  $  AIR ACCESS

  V/D 2 LOCAL 2 0 15 10000 20 12000 25  $  AIRPORTS

  V/D 3 ARTERIAL 2 0 .143 10000 .143 20000 .143  $  AIR LANES

  V/D 4 ARTERIAL 2 0 .75 20000 1.50 25000 2.0  $  RAIL LINES

  V/D 5 LOCAL 2 0 10 20000 10 40000 10  $  STATIONS

$  FOR DUMMY LINKS

  V/D 6 LOCAL 2 0 1 20000 1 40000 1

EDIT VOL/DELAY SET

         FUNCTION    1 HAS NO ERRORS
         FUNCTION    2 HAS NO ERRORS
         FUNCTION    3 HAS NO ERRORS
         FUNCTION    4 HAS NO ERRORS
         FUNCTION    5 HAS NO ERRORS
         FUNCTION    6 HAS NO ERRORS

VOLUME DELAY SET EXAMPLE  HAS BEEN READ

STORE VOL/DELAY SET
VOLUME DELAY SET EXAMPLE  HAS BEEN STORED ON DISK.

EJECT
```

```
READ MODAL SERVICE DATA SET '2/MODES', MODES 2 DISTRICTS 3

DATA FOR MODE 1, 'AIR'

FARE FROM ORIGIN 1 TO 2 17 TO 3 15

FARE FROM ORIGIN 2 TO 1 17 TO 3 16

FARE FROM ORIGIN 3 TO 1 15 TO 2 16

FREQUENCY FROM ORIGIN 1 TO 2 15 TO 3 11

FREQUENCY FROM ORIGIN 2 TO 1 15 TO 3 18

FREQUENCY FROM ORIGIN 3 TO 1 11 TO 2 18

DATA FOR MODE 2, 'RAIL'

FARE FROM ORIGIN 1 TO 2 6.2 TO 3 4.2

FARE FROM ORIGIN 2 TO 1 6.2 TO 3 5.5

FARE FROM ORIGIN 3 TO 1 4.2 TO 2 5.5

FREQUENCY FROM ORIGIN 1 TO 2 25 TO 3 17

FREQUENCY FROM ORIGIN 2 TO 1 25 TO 3 30

FREQUENCY FROM ORIGIN 3 TO 1 17 TO 2 30

SYSTEM POLICIES MODE 'AIR' SUBSIDY 500000, FIXED COST 1500000,  -
     VARIABLE COST RATE .05 TAX RATE .05

SYSTEM POLICIES MODE 'RAIL' SUBSIDY 10000, FIXED COST 5000000,  -
     VARIABLE COST RATE .02 TAX RATE 0

EDIT MODAL DATA SET

MODAL FILE MEMBER 2/MODES  HAS BEEN STORED ON DISK

EJECT




READ ACTIVITY SYSTEM DATA SET 'DOT', DISTRICTS 3

DISTRICT 1 4000 2000 8000 'DIST1'

DISTRICT 2 2700 2200 4500 'DIST2'

DISTRICT 3 3600 1900 10000 'DIST3'

EDIT ACTIVITY SYSTEM DATA SET


THE NUMBER OF DISTRICTS =     3
 ******  DISTRICT FILE MEMBER DOT      HAS BEEN STORED ON DISK.

PARAMETER 'NORMAL'

MODAL SPLIT PARAMETERS 'B-Q' 4.5E4 .5 .5 .5 .5 -2.09 -2.18 -.955 -2.24 0 .44

DISTRICT GROWTH PARAMETERS 'EXAMPLE' ACCESS 1 POPULATION GROWTH .02  -
     REGIONAL PRODUCT GROWTH .035
```

```
INCREMENT 25 PERCENT
STOP DEFINITICN OF PARAMETERS
 ******  ENC OF CURRENT DEFINITICN OF PARAMETER NORMAL

 ******  MOCAL SPLIT DATA B-Q      HAS BEEN STORED ON DISK.

 ******  DISTRICT GROWTH DATA EXAMPLE  HAS BEEN STORED ON DISK.

EJECT




$   RUN 2
$   SET UP THE BASE ACTION
ACTION 'BASE'
STRATEGY 'TEST' STAGE 1 YEAR 1965
DESCRIPTORS CF ACTION FOLLOW
NETWORK 'EXAMPLE'
DISTRICT DATA 'DOT'
MODE DATA '2/MODES'
VOL/DELAY DATA 'EXAMPLE'
STOP DEFINITICN CF ACTION
 ******  ENC OF CURRENT DEFINITION OF ACTION BASE

$   PREDICT BASE CCNSEQUENCES
PREDICT CONSEQUENCES 'BASE', ACTION 'BASE', PARAMETERS 'NORMAL'
STOP PREDICTICN CF CCNSEQUENCES
 ******  ENC OF DEFINITION OF CONSEQUENCE BASE


    THE NETWORK IS COMPLETELY ASSIGNED AFTER   218 ITERATIONS
             TIME USED SINCE START OF RUN IS   0.08 MINUTES

DATA HAS BEEN STORED ON DISK IN DATA FILE BASE
```

```
                    FINAL OUTPUT

      TRAVEL TIME OUTPUT BASE     FOR NETWORK EXAMPLE

                   OUTPUT ON DISK

VALUATION FILE MEMBER BASE     HAS BEEN STORED ON DISK.

 ******  BASIC DECISION MODULE      1

 ******        ACTIONS  BASE
 ******        PARMETER NORMAL
 ******        CONSENCE BASE




 $    RUN 3

 $    OUTPUTS FROM CONSEQUENCE BASE

 LOAD FLOW DATA 'BASE'

 $    TRIP VOLUMES

 REQUEST CONSEQUENCES, INTERZONAL TRIPS FOR ALL ZONES
                                 TOTAL INTERZONAL TRIPS ASSIGNED

                                  FLOW PATTERN NAME IS BASE

                                   DISTRICT         DISTRICT
                                    NUMBER            NAME

                                       1            DIST1
                                       2            DIST2
                                       3            DIST3


                      THIS IS THE MATRIX FOR      3 DISTRICTS AND    2 MODES
                          WHICH GIVES THE ASSIGNED INTERZONAL VOLUMES
                         FOR ALL DISTRICT PAIRS, IN PASSENGERS PER DAY.

                                      AIR      MODE TRIPS


  TO DISTRICT    1          2          3
FROM DISTRICT
    1            0        540        512
    2          539          0        518
    3          511        518          0
```

RAIL MODE TRIPS

TO DISTRICT FROM DISTRICT	1	2	3
1	0	2227	6378
2	2227	0	3246
3	6378	3246	0

$ TRAVEL TIMES

REQUEST CONSECUENCES, TRAVEL TIMES FOR ALL ZONES

FINAL OUTPUT

TRAVEL TIME OUTPUT FOR NETWORK EXAMPLE

THIS IS THE TABLE TO CONVERT MACHINE NODE NUMBERS TO USER NODE NUMBERS

MACHINE NUMBERS	1	2	3	4	5	6
0 USER NUMBERS	1001	1002	1003	2001	2002	2003

THE FOLLOWING MATRIX USES MACHINE NODE NUMBERS

THIS IS THE MATRIX FOR 6 ZONES WHICH GIVES THE TRAVEL TIMES
BETWEEN ALL ZONE PAIRS IN MINUTES.

TO ZONE FROM NODE	1	2	3	4	5	6
1	0.0	56.84	50.84	160.00	252.68	224.52
2	56.84	0.0	57.48	216.84	309.52	281.36
3	50.84	57.48	0.0	210.84	303.52	275.36
4	160.00	216.84	210.84	0.0	92.68	64.52
5	252.68	309.52	303.52	92.68	0.0	82.28
6	224.52	281.36	275.36	64.52	82.28	0.0

$ ACCESSIBILITIES

REQUEST CONSECUENCES, ACCESSIBILITIES

ACCESSIBILITIES FOR FLOW PATTERN BASE

NETWORK EXAMPLE

ORIGIN DISTRICT	AIR	MODE RAIL	ALL MODES
DIST1	1.17617E 03	9.62068E 03	1.07969E 04
DIST2	1.37145E 03	7.10120E 03	8.47266E 03
DIST3	1.24419E 03	1.16366E 04	1.28808E 04
ALL ORIGINS	1.25114E 03	9.66484E 03	1.09160E 04

$ LINK FLOW CATA

REQUEST CONSEQUENCES, LINK VOLUMES,SPEEDS,AND TIMES FOR ALL LINKS

LINK TABLE
THIS TABLE IS FOR ALL LINKS IN NETWORK EXAMPLE

LINK FROM	TO	TRAFFIC VOLUME (PASSENGERS PER DAY)	SPEED (MILES PER HOUR)	TRAVEL TIME (MINUTES)
1001	1101	1052	56.8	5.28
1001	2001	0	60.0	160.00
1002	1102	1057	57.0	10.52
1003	1103	1029	57.1	7.36
2001	2101	8605	6.0	10.00
2001	1001	0	60.0	160.00
2002	2102	5473	6.0	10.00
2003	2103	9624	6.0	10.00
1101	1001	1050	56.8	5.28
1101	1201	1052	3.9	15.52
1102	1002	1058	57.0	10.52
1102	1202	1057	3.9	15.52
1103	1003	1030	57.1	7.36
1103	1203	1029	3.9	15.52
1301	1101	1050	3.9	15.52
1302	1102	1058	3.9	15.52
1303	1103	1030	3.9	15.52
1201	1302	540	420.0	10.00
1201	1303	512	419.0	7.16
1202	1301	539	420.0	10.00
1202	1303	518	420.6	8.56
1203	1301	511	419.0	7.16
1203	1302	518	420.6	8.56
2101	2001	8605	6.0	10.00
2101	2103	6378	60.6	44.52
2101	2202	2227	72.0	58.36
2102	2002	5473	6.0	10.00
2102	2202	5473	62.8	14.32
2103	2003	9624	6.0	10.00
2103	2202	3246	68.8	47.96
2103	2101	6378	60.6	44.52
2202	2101	2227	72.0	58.36
2202	2102	5473	62.8	14.32
2202	2103	3246	68.8	47.96

COST SUMMARIES FOR FLOW PATTERN BASE

NETWORK EXAMPLE

DAILY USER DATA BY MODE AND ORIGIN

MODE	ORIGIN DISTRICT	TOTAL TRIPS (PASS/DAY)	USER FARES TOTAL ($)	USER FARES AVERAGE ($/TRIP)	USER TRAVEL TIME TOTAL (HOURS)	USER TRAVEL TIME AVERAGE (MIN/TRIP)
AIR	DIST1	1052	1.68600E 04	16.03	9.45395E 02	54.
AIR	DIST2	1057	1.74510E 04	16.51	1.00686E 03	57.
AIR	DIST3	1029	1.59530E 04	15.50	9.29231E 02	54.

RAIL	DIST1	8605	4.05950E 04	4.72	1.02984E 04	72.
RAIL	DIST2	5473	3.16604E 04	5.78	7.89132E 03	87.
RAIL	DIST3	9624	4.46406E 04	4.64	1.13098E 04	71.

USER WAIT TIME		WEIGHTED COSTS	
TOTAL (HOURS)	AVERAGE (MIN/TRIP)	TOTAL ($)	AVERAGE ($/TRIP)
1.18865E 03	67.79	2.11281E 04	20.08
9.31839E 02	52.90	2.13284E 04	20.18
1.08334E 03	63.17	1.99781E 04	19.42
6.68528E 03	46.61	7.45624E 04	8.67
2.84083E 03	31.14	5.31247E 04	9.71
6.96061E 03	43.40	8.11814E 04	8.44

DAILY USER DATA BY MODE

MODE	TOTAL TRIPS (PASS/DAY)	USER FARES		USER TRAVEL TIME	
		TOTAL ($)	AVERAGE ($/TRIP)	TOTAL (HOURS)	AVERAGE (MIN/TRIP)
AIR	3138	5.02640E 04	16.02	2.88148E 03	55.
RAIL	23702	1.16896E 05	4.93	2.94996E 04	75.
TOTALS	26840	1.67160E 05	6.23	3.23810E 04	72.

USER WAIT TIME		WEIGHTED COSTS	
TOTAL (HOURS)	AVERAGE (MIN/TRIP)	TOTAL ($)	AVERAGE ($/TRIP)
3.20384E 03	61.26	6.24346E 04	19.90
1.64867E 04	41.74	2.08868E 05	8.81
1.96906E 04	44.02	2.71303E 05	10.11

YEARLY COSTS AND REVENUES BY MODE

MODE	TOTAL TRIPS	USER FARES	TOTAL USER COSTS	OPERATOR'S PROFIT
AIR	1145370	1.83464E 07	2.27886E 07	1.20273E 07
RAIL	8651230	4.26670E 07	7.62370E 07	2.70595E 07
TOTALS	9796600	6.10134E 07	9.90256E 07	3.90868E 07

GOVERNMENT REVENUE	OPERATOR'S PROFIT PER PASSENGER	GOVT. REVENUE PER PASSENGER
4.17318E 05	10.50	0.36
-1.00000E 04	3.13	-0.00
4.07318E 05	3.99	0.04

```
WRITE EVALUATION RESULTS FOR GOAL FABRIC 'EXAMPLE', VARIABLES ALL
     UTILITIES ALL CONSEQUENCES 'BASE'
```

GOAL VARIABLE NAME	UTILITY FUNCTION NAME	CONSEQUENCE FILE NAME	VALUE	
AVEFARE	2-ONES	BASE	6.23	
AVETIME	2-ONES	BASE	72.39	
TOTTRIP	ONE	BASE	3138.00	MODE AIR
TOTTRIP	ONE	BASE	23702.00	MODE RAIL
TOTTRIP	ONE	BASE	26840.00	MODE ALL

```
$   RUN 4
$    DEFINITION AND EVALUATION OF A GOAL FABRIC
GOAL FABRIC 'EXAMPLE'
'AVEFARE' = AVERAGE INTERDISTRICT FARES, TRIPS
'AVETIME' = AVERAGE INTERDISTRICT TIMES, TRIPS
'TOTTRIP' = SUM INTERDISTRICT
     TRIPS
     END
```

```
STOP DEFINITION OF GOAL FABRIC

 ******  END OF CURRENT DEFINITION OF GOAL FABRIC EXAMPLE

UTILITY FUNCTION 'ONE', 1 VALUE, 1

 ******  UTILITY VECTOR ONE      HAS BEEN DEFINED WITH  1 VALUES

UTILITY FUNCTION '2-ONES', 2 VALUES, 1 1

 ******  UTILITY VECTOR 2-ONES   HAS BEEN DEFINED WITH  2 VALUES

$

EVALUATE GOAL FABRIC 'EXAMPLE', CONSEQUENCES 'BASE'

UTILITY 'ONE'

'TOTTRIP' FROM ALL TO ALL BY EACH

 ******  GOAL VARIABLE TOTTRIP  HAS BEEN EVALUATED WITH UTILITY ONE

'TOTTRIP' FROM ALL TO ALL BY ALL

 ******  GOAL VARIABLE TOTTRIP  HAS BEEN EVALUATED WITH UTILITY ONE

UTILITY '2-ONES'

'AVEFARE' FROM ALL TO ALL BY ALL

 ******  GOAL VARIABLE AVEFARE  HAS BEEN EVALUATED WITH UTILITY 2-ONES

'AVETIME' FROM ALL TO ALL BY ALL

 ******  GOAL VARIABLE AVETIME  HAS BEEN EVALUATED WITH UTILITY 2-ONES

STOP EVALUATION OF GOAL FABRIC




$   RUN 5

MODIFY NETWORK 'EXAMPLE' FORMING 'FUTURE'

$  ADD NEW DIRECT RAIL LINK BETWEEN DISTRICTS 1 AND 2, DISTANCE 80

ADD LINKS 2101 2102 80 1 4, 2102 2101 80 1 4

$  CHANGE AIRPORT DESIGN AND PROCEDURES, REDUCING DELAYS IN HALF

CHANGE LINKS 1001 1101 .5 1 1, 1101 1001 .5 1 1, 1002 1102 .5 1 1  -
     1102 1002 .5 1 1 , 1003 1103 .5 1 1,  1103 1003 .5 1 1

EDIT NETWORK

STORE NETWORK

NETWORK FUTURE   HAS BEEN STORED ON DISK.
```

```
MODIFY MODAL SERVICE DATA '2/MODES'

$   DOUBLE RAIL FREQUENCIES BETWEEN 1 AND 2, TO 50

MODE 2 FREQUENCY 1 2 50

MODE 2 FREQUENCY 2 1 50

$  REDUCE RAIL FARES BY 1.00 BETWEEN 1 AND 2, TO 5.25

MODE 2 FARE 1 2 5.25

MODE 2 FARE 2 1 5.25

EDIT MODAL SERVICE DATA

STORE MODAL DATA 'CHANGED'

MODAL FILE MEMBER CHANGED  HAS BEEN STORED ON DISK

$  INCREASE DISTRICT 2 INCOME TO $2300.

MODIFY ACTIVITY SYSTEM DATA 'DOT'

DISTRICT 2 POPULATION 2700 INCOME 2300 HOLD/CAP 4500 NAME 'DIST2'

EDIT ACTIVITY SYSTEM DATA

STORE ACTIVITY SYSTEM DATA 'DOT-2'
 ******  DISTRICT FILE MEMBER DOT-2    HAS BEEN STORED ON DISK.

EJECT




$  RUN 6

$  PREDICT CONSEQUENCES FOR PROPOSED CHANGES

ACTION 'PRUPOSED'

STRATEGY 'TEST' STAGE 2 YEAR 1975

INCLUDES 'BASE'

DESCRIPTORS OF ACTION FOLLOW

NETWORK 'FUTURE'

DISTRICT DATA 'DOT-2'

MODE DATA 'CHANGED'

VOL/DELAY DATA 'EXAMPLE'

STOP DEFINITION OF ACTION

 ******  END OF CURRENT DEFINITION OF ACTION PROPOSED
```

```
PREDICT CONSEQUENCES 'PROPOSED', ACTICN 'PROPOSED',PARAMETERS 'NORMAL'
DISTRICT DATA 'DCT-3' YEAR 1980
STOP PREDICTICN CF CCNSEQUENCES
 ******  ENC OF CEFINITION OF CONSEQUENCE PROPOSED
```

THE NETWORK IS COMPLETELY ASSIGNED AFTER 230 ITERATIONS

TIME USED SINCE START OF RUN IS 0.09 MINUTES

DATA HAS BEEN STORED ON DISK IN DATA FILE PROPOSED

FINAL OUTPUT

TRAVEL TIME OUTPUT PROPOSED FOR NETWORK FUTURE

OUTPUT ON DISK

VALUATION FILE MEMBER PROPOSED HAS BEEN STORED ON DISK.

ACTIVITY SYSTEM PREDICTIONS

FOR VALUATION DATA PROPOSED

BASED ON BASE

ORIGIN DISTRICT	EASE YEAR FCPULATION IN MILLIONS	PREDICTED PCPULATION IN MILLIONS	PERCENT INCREASE
DIST1	4.000	4.411	10.28
DIST2	2.700	2.885	6.85
DIST3	3.600	4.034	12.05

BASE YEAR PER CAPITA INCOME	PREDICTED PER CAPITA INCOME	PERCENT INCREASE
2000.	2170.	8.51
2300.	2575.	11.97
1900.	1916.	0.87

REGIONAL TOTALS

	BASE YEAR	PREDICTION	PERCENT INCREASE
POPLLATICN IN MILLICNS	10.300	11.330	10.00
NET REGICNAL PRODUCT (BILLICNS OF DOLLARS)	21.050	24.734	17.5C

```
$  RUN 7

$  COMPARE BASE AND PROPOSED

COMPARE TRIPS AND SURPLUSES, VALUATION 'PROPOSED' AND VALUATION 'BASE'  -
    TIME VALUE 2.35 WAIT FACTOR .40
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COMPARISON OF VALUATION FILES PROPOSED AND BASE

FLOW PATTERNS PROPOSED AND BASE

VALUES SHOWN ARE (FILE PROPOSED) - (FILE BASE   )

CHANGE IN TRIPS

ORIGIN DISTRICT	AIR	MODE RAIL	ALL MODES
DIST1	594	1555	2149
DIST2	790	1689	2479
DIST3	856	-68	788
ALL ORIGINS	2240	3176	5416

CHANGE IN CONSUMER TRAVEL TIME SURPLUS
(PASSENGER-HOURS PER DAY)

ORIGIN DISTRICT	AIR	MODE RAIL	ALL MODES
DIST1	2.80417E 02	-2.91191E 02	1.21923E 02
DIST2	3.63478E 02	1.08797E 02	6.69151E 02
DIST3	3.22553E 02	3.52830E 01	6.41798E 02
ALL ORIGINS	9.66448E 02	-1.47111E 02	1.43287E 03

CHANGE IN CONSUMER TRAVEL COST SURPLUS
(DOLLARS PER DAY)

ORIGIN DISTRICT	AIR	MODE RAIL	ALL MODES
DIST1	6.70424E 01	1.09129E 03	-2.55107E 03
DIST2	1.09161E 02	2.65572E 03	-8.79294E 02
DIST3	-7.34978E 01	-7.29738E 01	-8.34360E 03
ALL ORIGINS	1.02706E 02	3.67404E 03	-1.17740E 04

CHANGE IN CONSUMER WAITING TIME SURPLUS
(PASSENGER-HOURS PER DAY)

ORIGIN DISTRICT	AIR	MODE RAIL	ALL MODES
DIST1	-1.95055E 01	2.24418E 03	1.99488E 03
DIST2	2.91071E 01	1.50734E 03	1.30310E 03
DIST3	6.23613E 01	3.43440E 01	-3.02662E 02
ALL ORIGINS	7.19629E 01	3.78587E 03	2.99532E 03

```
                         CHANGE IN CONSUMER WEIGHTED FRICTION SURPLUS
                          (WEIGHTED FRICTION = TRAVEL COST SURPLUS
                                +    2.35 * TRAVEL TIME SURPLUS
                                +    0.94 * WAITING TIME SURPLUS)

 CRIGIN                    MODE
DISTRICT   AIR            RAIL          ALL MODES

DIST1      7.18219E 02   1.30466E 03  -1.46660E 03
DIST2      9.74977E 02   3.51433E 03   1.21445E 03
DIST3      7.C9446E 02   2.36788E 01  -6.95644E 03

  ALL
ORIGINS    2.40264E 03   4.84267E 03  -7.20858E 03


  CCMPARE GOAL FABRIC 'EXAMPLE'


  BASE CCNSECUENCE 'PASE'

  CCNSEQUENCE SFT 'PCTH'

  BASE UTILITY 'ONE'

                                                                DIFFERENCE - BASE

GOAL VARIABLE     CCNSEQUENCE          VALUE       RANKING      ABSOLUTE   PERCENT

***  TOTTRIP    ******

   ORIGIN ALL
   DEST   ALL
   MODE   AIR     BASE                3138.00          2           0.0        0.0

                  PROPOSED            5378.00          1        2240.CC     71.38


   ORIGIN ALL
   DEST   ALL
   MODE   RAIL    BASE               23702.CO          2           0.0        0.0

                  PROPOSED           26878.00          1        3176.CC     13.40

***  TOTTRIP    ******

   ORIGIN ALL
   DEST   ALL
   MODE   ALL     BASE               26840.00          2           0.0        0.0

                  PROPOSED           32256.CC          1        5416.CC     20.18

***  AVEFARE    ******

   ORIGIN ALL
   DEST   ALL
   MODE   ALL     BASE                   6.23          2           0.0        0.0

                  PROPOSED               6.68          1           0.45       7.29

***  AVETIME    ******
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```
ORIGIN ALL
DEST   ALL
MODE   ALL     BASE                        72.39        1                       0.C      C.0

               PROPOSED                    69.93        2                      -2.46    -3.40

    STEP COMPARISON CF GCAL VARIABLES

     ******  END CF GCAL FABRIC CCMPARISON

    EJECT
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A Proposed Method of Regulating Vehicle Weights in Ontario

M. D. ARMSTRONG, F. W. JUNG, and W. A. PHANG,
Department of Highways, Ontario

The proposed new method of vehicle weight regulation, which uses basic axle weights and a "bridge formula", was developed to permit vehicles to carry the greatest possible payload without causing abnormal damage to pavement and bridge structures constructed to present standards. Vehicle weight surveys undertaken in 1967 showed that gross weights were close to their allowable values but individual axle weights frequently exceeded their legal limits, and that some vehicles with closely spaced axles could be harmful to bridges. Basic weights on axle units of 20 kips for single axles and 35 kips for dual axles of 4-ft minimum spacing are used in conjunction with a bridge formula that limits the weights on any axle group comprising a vehicle by the equation $W_m = 20 + 2.07\ B_m - 0.0071\ B_m^2$. The equivalent base length, B_m, varies between about 1 and 1.75 times the actual base length, or the extreme-axle distance of the group, and depends on the pattern of load distribution. A mathematical relationship was established between the bridge formula and the normal live load capacity of bridges in terms of their span lengths. Bridges designed for H20 or heavier standard loads were tested against this relationship and were found to be not overstressed beyond acceptable limits. The proposed method will permit most vehicles to carry higher payloads, and only very few vehicles or trains would have their gross weights reduced. The importance of enforcement in the regulatory system is emphasized.

•LOAD RESTRICTIONS were first applied to vehicles using the roads of Ontario in 1916, when single-axle loads were limited to 9,000 lb (9 kips). Since then there have been several changes until, in 1961, the 18-kip limit (32-kip dual axles) was set for all King's highways. Gross vehicle weights presently permitted in Ontario are shown in Figure 1.

Although permissible loads have been raised at intervals since restrictions were introduced in 1916, periodic representations have been made by the trucking industry and certain other industrial interests in the province in favor of higher gross loads. The frequency of these representations has increased in recent years.

In response to these representations, several special studies have been undertaken by the Department of Highways. The first of these was a benefit-cost study made in 1966 in conjunction with the (then) Department of Economics and Development (1, 2). In this study, the economics of raising the basic single-axle load to various levels was investigated and it was found, for example, that the annual return in the form of reduced operating costs for the trucking industry would amount to less than 4 percent of the cost of upgrading the road system to accept traffic with a legal single-axle load of 20 kips.

It was concluded that a general arbitrary increase in permissible axle loads could not be entertained, but in-depth studies of vehicle loading and the effects of loads on pavements and bridges were instituted in order to see if any other changes could be

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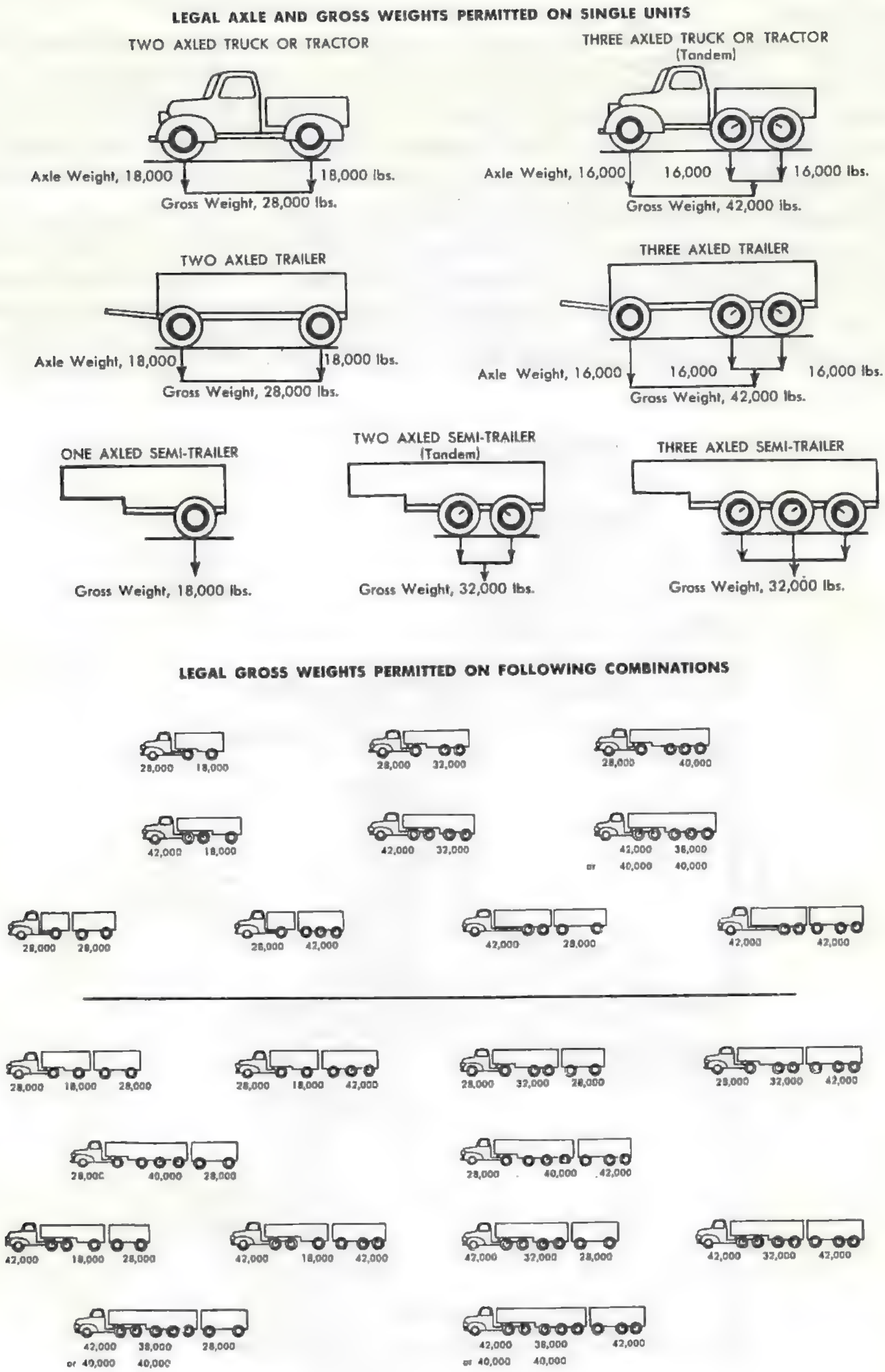


Figure 1. Permissible weights on motor vehicles in Ontario.

made to ensure that commercial vehicles could be licensed for normal operation at the absolute maximum loads consistent with the protection of the highway system from abnormal damage.

In 1967, a survey of 6,700 trucks was made to determine their gross weights, the loads on their axles, and the spacing of their axles. Some of the results of this survey appear in Figures 2, 3, and 4. They show that the actual gross weights were usually very close to the registered gross weights but the nominal maximum axle-loads were frequently exceeded. The survey also revealed a large proportion of very short vehicles with closely spaced axles that can be very damaging to bridge structures. This reflects the lack of axle spacing control in the regulations.

The general compliance with gross weight regulations and general disregard for axle-weight restrictions revealed by the 1967 survey are not too surprising, because only the gross weight restrictions have been enforced in the past. This has led to the development of a spectrum of actual axle loadings that ranges far beyond the legal maximum axle load. In other words, as a direct result of the province's enforcement practices, the roads and bridges have been subjected to a large degree of overloading of axles, but

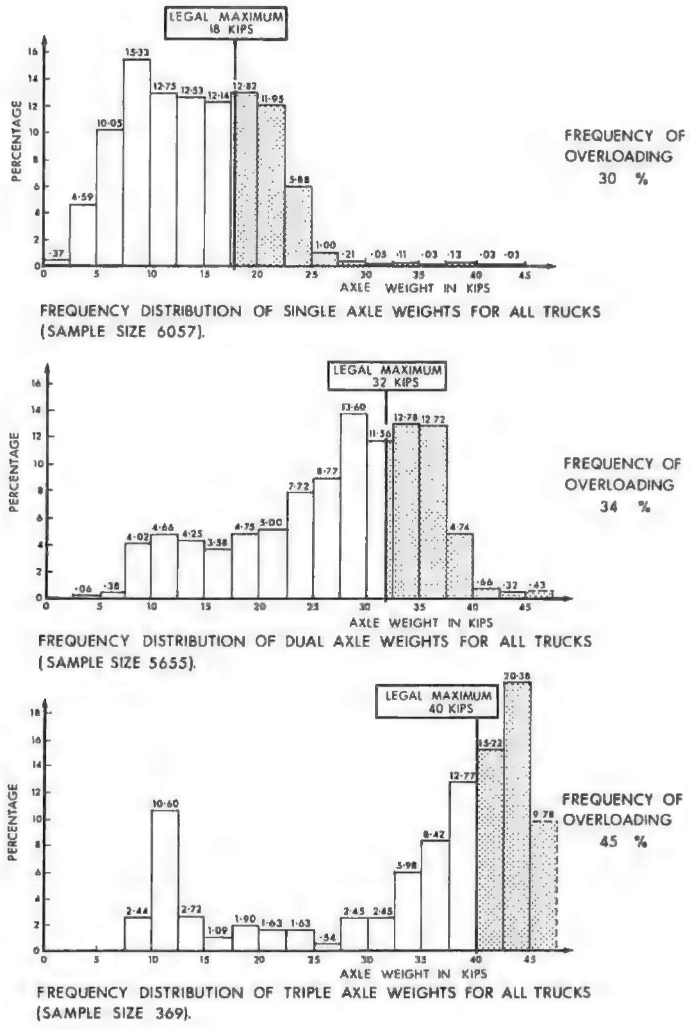
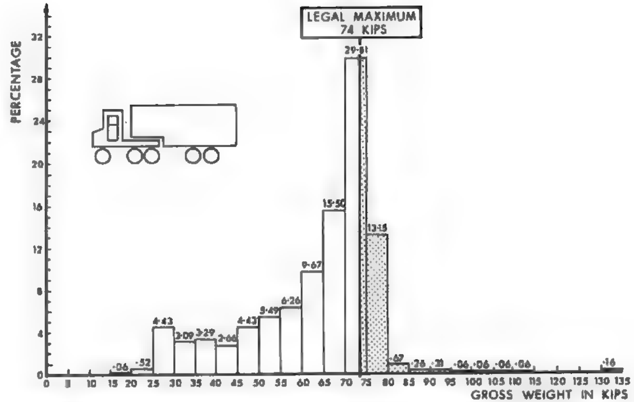
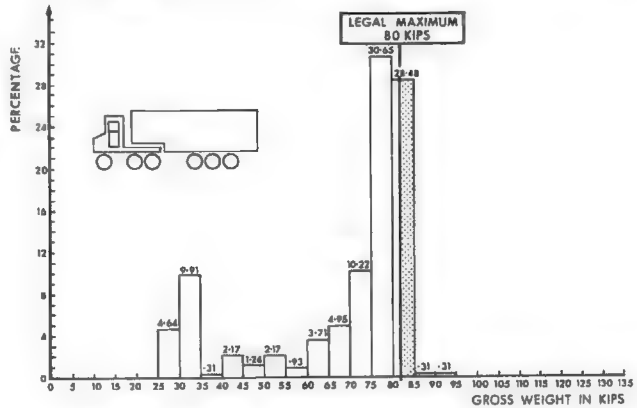


Figure 2. Selected data from survey of all trucks, 1967.

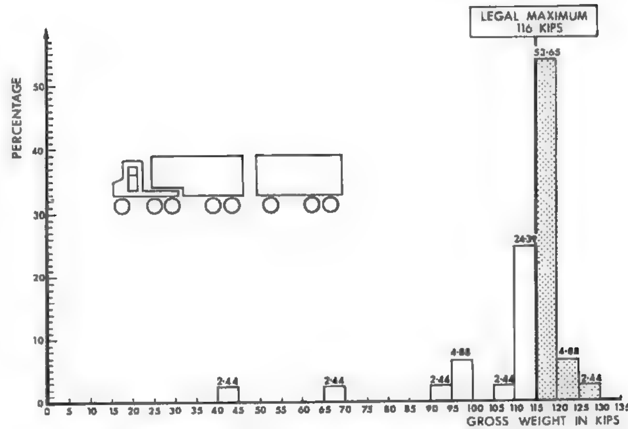


FREQUENCY DISTRIBUTION OF GROSS VEHICLE WEIGHTS FOR 3-S2 TYPE TRUCKS (SAMPLE SIZE 1915).

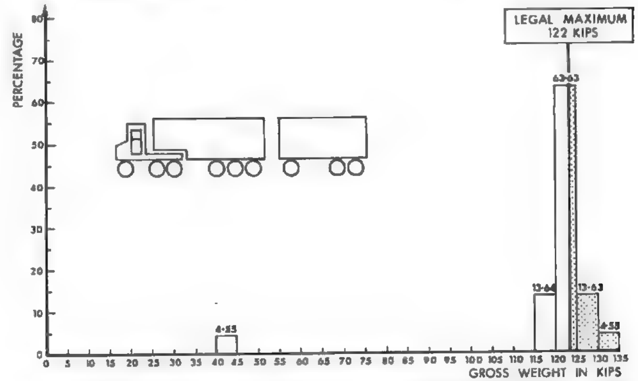


FREQUENCY DISTRIBUTION OF GROSS WEHICLE WEIGHTS FOR 3-S3 TYPE TRUCKS (SAMPLE SIZE 324).

Figure 3. Selected data from survey of 3-S2 and 3-S3 trucks, 1967.



FREQUENCY DISTRIBUTION OF GROSS VEHICLE WEIGHTS FOR 3-S2-3 TYPE TRUCKS (SAMPLE SIZE 41)



FREQUENCY DISTRIBUTION OF GROSS VEHICLE WEIGHTS FOR 3-S3-3 TYPE TRUCKS (SAMPLE SIZE 22).

Figure 4. Selected data from survey of 3-S2-3 and 3-S3-3 trucks, 1967.

the gross vehicle loads have been held close to the legal limits. It should be appreciated, however, that the legal limits, even in the case of long trains, are in excess of the current standard bridge design live load (HS truck of 72 kips). This state of affairs raises an interesting possibility in the field of load legislation that can be expressed in the following question: If the method of enforcement could be so changed as to ensure that the actual range of loads revealed by the 1967 survey remains unchanged, what benefits, immediate and potential, would accrue to the trucking industry in the form of increased load-carrying capacity, if the basic legal single-axle load was increased from 18 kips to 20 kips and axle-spacing control was introduced?

In exploring this possibility, a new method of vehicle weight regulation was developed that offers, for the first time, a rational way to balance the conflicting interests of the trucking industry and highway authorities. The method permits every truck to carry the greatest possible payload without causing abnormal damage to pavement and bridge structures with consequent premature depreciation of the provincial investment in highway plant. Implementation of the proposed new method, however, will involve strict enforcement of axle load and axle spacing requirements, as well as gross weight limits.

The new method is presented in this paper together with a limited discussion of the impact it would have on existing vehicle fleets and its possible effect on vehicle design in the future. It should be noted, however, that no discussion is included on other factors having an important bearing on allowable loading of vehicles, such as power/weight ratio and weight/braking capacity factors.

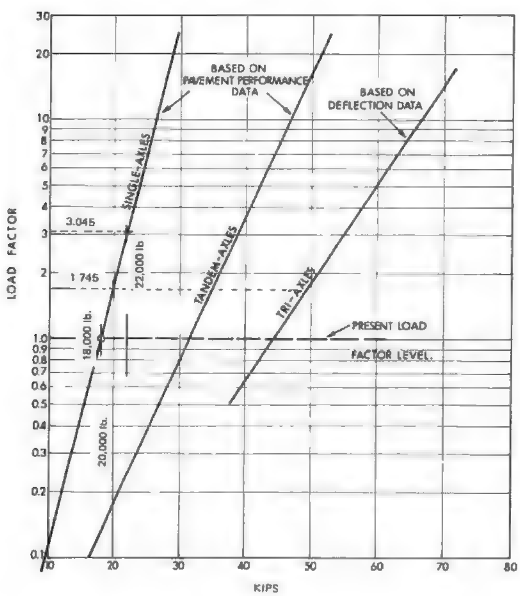
PROPOSED NEW METHOD

The proposed new method of weight regulation is based on the controlling factors in the protection of pavements and bridge structures. Under normal operating conditions, the basic axle weight is the important factor for pavements, but both axle weight and axle spacing are important for bridges and a bridge formula is introduced by which they can be controlled.

Basic Axle Weights

The 1967 truck survey revealed a startlingly high frequency of overloaded axles. Thirty percent of single axles and 34 percent of dual axles were found to be overloaded, even though the gross weights on which enforcement has customarily been based were often not exceeded. Compared with the legal limits of 18,000 lb on a single axle and 32,000 lb on a dual axle that had been in force since 1961, 15 percent of the single-axle weights recorded in the survey exceeded 21,000 lb and 2 percent exceeded 25,000 lb. For dual axles 15 percent exceeded 35,000 lb and 2 percent exceeded 40,000 lb.

Although certain instances of pavement deterioration caused by excess loads had occurred, undue and widespread damage was not being caused by the regime of vehicle axle and gross weights that was actually using the highways. This confirmed other studies indicating that pavements might tolerate greater axle loads. Accordingly, increased basic axle weights are being proposed. These have been set at a level that, given effective enforcement,



EQUIVALENT AXLE LOADS (lb)

SINGLE -AXLE LOAD	TANDEM	DERIVED TRI-AXLE	LOAD FACTOR
18,000	32,000	44,000	1.000
20,000	35,000	50,000	1.745
22,000	39,000	56,000	3.045
24,000	43,000	61,000	6.312
26,000	47,000	65,000	9.269

Figure 5. Load equivalency factors and axle load equivalents for flexible pavements.

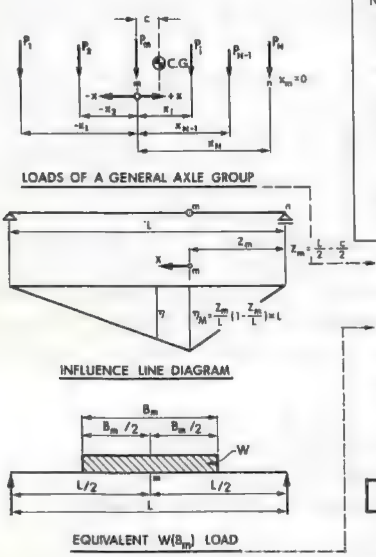
should ensure that the present pattern of loads would not be raised to a damaging level in the future. The concept of equivalent axle loads in terms of their damaging effect on pavements, developed at the AASHO Test Road and shown in Figure 5, was utilized together with the 85 percentile weight level determined in the survey in fixing the basic axle loads on single- and dual-axle units. The basic triple-axle weight was found to be governed by the bridge formula described later.

The new proposed basic axle weights are 20,000 lb for single axle (presently 18,000 lb), 35,000 lb for dual axle (presently 32,000 lb), and 44,000 lb for triple axle (presently 40,000 lb). This represents an increase of about 10 percent, and increased weights can also be allowed on steering axles, provided the design and safe control of the vehicle permit.

Bridge Formula

Stresses generated in bridge structures depend not only on the gross weight of a vehicle but also on the distribution of axle weights and interaxle spacings. Truck operators usually prefer short trucks because of their smaller weight and good maneuverability. However, the high concentration of load associated with short vehicles may cause overstresses in bridges which are neither anticipated by design nor sufficiently checked by current regulations.

Equivalent Base Length—There is an infinite number of possible axle weight distributions and axle space combinations, which are mathematically untreatable because of their discontinuity. A method is therefore needed by which any axle configuration can be transformed into simple and continuous load patterns. To achieve this, the concept of "equivalent base length" has been developed (4, 5). The equivalent base length (B) is defined as a length on which the gross vehicle or axle group weight (W) must be continuously and uniformly distributed to cause the same moment or shear in the bridge structure as the actual vehicle or axle group. Depending on the shape of influence lines, the equivalent base length is a function of the bridge span length. But, in most practical cases, the effect of span length is small and can safely be neglected, so that the transformation of vehicles into simple W-B load patterns is then independent from structural properties and dimensions. The concept was developed for maximum moments in simply supported span bridges, but subsequent investigations have shown that the concept remains acceptably valid also for other types of structures. The derivation of the equivalent base length is shown in Figure 6.



NOTATION:

- W = total weight of an axle group
- b = base length of an axle group, distance between first and last axle
- c = distance of the centre of gravity from the axle load P_m, under which the maximum moment will occur, usually the axle closest to the centre of gravity
- N = number of axles in a group, (count '2' for dual and '3' for triple axles)
- B_m = equivalent base length, the length over which the total weight must be uniformly distributed in order to generate the same maximum bending moment (m) in a simply supported beam as the axle group itself.
- L = span length of the beam
- M_m = maximum bending moment

$z_m = \frac{L}{2} - \frac{c}{2}$

Moment due to axle group:

$$M_m = \frac{WL}{4}\left[1 - \alpha\left(\frac{b}{L}\right) + \beta^2\left(\frac{b}{L}\right)^2\right] \qquad \text{where: } \alpha = \frac{2\sum_{i=1}^{N} P_i|x_i|}{Wb}$$

$$\beta = \frac{\sum_{i=1}^{N} P_i\, x_i}{Wb} = \frac{c}{b}$$

Moment due to equivalent $W(B_m)$ - Load:

$$M_m = \frac{WL}{4}\left[1 - \frac{B_m}{2L}\right]$$

Equalizing these moments and solving for B_m

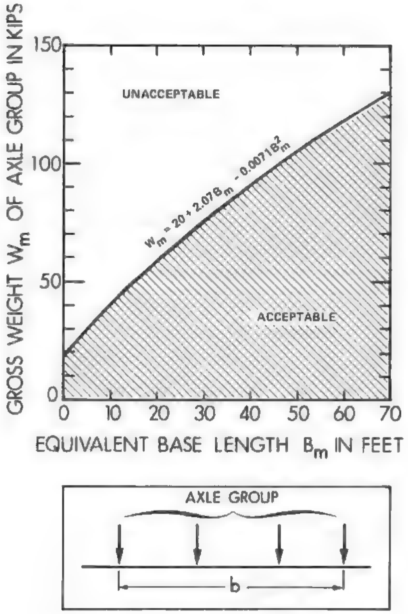
$$B_m = 2\left[\alpha - \left(\frac{b}{L}\right)\beta^2\right] b$$

A conservative estimate for the ratio $\frac{b}{L}$ is: $\frac{b}{L} \cong \frac{N-1}{N}$, with this:

$$\boxed{B_m \cong 2\left(\alpha - \frac{N-1}{N}\beta^2\right) \times b = K\,b}$$

The influence of the term with β^2 is about 7.5 percent for large c values. The most simplified form is therefore: $B_m = 1.85\ \alpha\ b$

Figure 6. Derivation of equivalent base length for simply supported beam moment.



EQUIVALENT BASE LENGTH B_m = Kb.

Figure 7. Acceptance test diagram.

Bridge Formula and Live Load Level for Normal Operation—A suitable format of a bridge formula consists of a permissible weight function $W_m = f(B_m) = W_o + CB_m - DB_m^2$, i.e., an equation by which the permissible weight W_m can be calculated (5). C and D are constants, W_o can be interpreted as the permissible weight on a single axle, and B_m is the equivalent base length for moments. Entrance value B_m is

$$B_m = K \times b$$

where

$$K = \frac{4 \sum_{i=1}^{N} P_i|x_i|}{b \sum_{i=1}^{N} P_i} - \frac{2(N-1)}{N} \times \left(\frac{\sum_{i=1}^{N} P_i x_i}{b \sum_{i=1}^{N} P_i} \right)^2$$

with reference to Figure 6. The actual formula that has been resolved for Ontario is shown in Figure 7; this formula has been used to calculate the loads that can be permitted on axle units with spacings greater than those of the basic axle units (Table 1, Appendix A) and the maximum gross weights that can be permitted on actual vehicles for the full range of equivalent base lengths (Table 2, Appendix A).

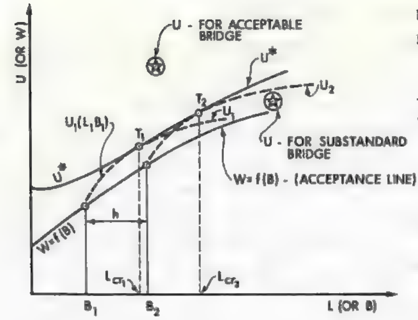
If such a function is used for vehicle weight regulation, it determines the limiting load level for normal operation of heavy vehicles, and it becomes necessary to establish its relationship to the normal operational live load capacity of bridge structures, so that the bridges can be rated in terms of this load level. The load function $W_m = f(B_m)$ must be transformed to make it suitable for application to structures by introducing the span length (L) as a variable. The new function has the form $U_m^* = f(L)$ where U_m^* is a total load that, when uniformly distributed over the full span (L), generates the same maximum moment as the load $W_m = f(B_m)$. The derivation of the function $U_m^* = f(L)$ is shown in Figure 8.

It should be noted that load functions $U^* = f(L)$ are in general also dependent on the shape of influence lines, much in the same way as the equivalent base length, and the same remarks apply as before. The function $U_m^* = f(L)$ can be understood as defining the permissible live load and, at the same time therefore, the minimum required live load capacity of simply supported bridges for the normal operation of heavy vehicles.

Load-Carrying Capacity of Bridges—The actual load-carrying capacity of a bridge depends on the cross-sectional properties and the stresses that the material of the structural member can endure. If these stresses are frequently exceeded, incremental damage will accumulate in the bridge and its service life will be reduced. Based on the AASHO road tests on bridges, the ACI recommendations, and the DIN standards prevailing in Europe, the following serviceability stress limits (normal operating conditions) were applied in this investigation:

Unwelded steel beams	85 percent of yield stress
Welded steel beams	75-80 percent of yield stress
Prestressed concrete	modulus of rupture
Reinforced concrete	73 percent of cylinder strength

With these limit stresses and the section modulus of the cross section, for instance, the load-carrying capacity for bending moment can be expressed in terms of a total load



NOTATION: (see also notations on Figure 5)

U = normal operational load capacity of a bridge structure

U_m, U_1, U_2 = maximum required normal operational load capacity in terms of total live load being equally distributed over the span L, for a selected pair of W_m and B (or B_m)

U^*_m, U^* = largest live load level due to legal, ordinary operation of heavy vehicles, or maximum required normal operational load capacity for the whole curve $W_m = f(B_m)$, also in terms of total live load equally distributed over the span L

W_m = permissible weight on axle group

For maximum bending moments: $U_m = \frac{8M_m}{L}$, and substituting M_m from Figure 5 (second equation):

$$U_m = W_m\left(2 - \frac{B_m}{L}\right) = f(B_m) \times \left(2 - \frac{B_m}{L}\right)$$

The equation has the same format in case of shear, and the solution for $U^*(L)$, omitting the index 'm', can be formed by:

$$F(L,U,B) = f(B) \times \left(2 - \frac{B}{L}\right) - U \equiv 0$$

$$\frac{\partial F}{\partial B} = \left(2 - \frac{B}{L}\right)\frac{df(B)}{dB} - \frac{f(B)}{L} \equiv 0$$

From these two equations the function $U^*(L)$ can be formed.

Assume the following format of acceptance line:

$$W = f(B) = W_o + CB - DB^2$$

then:

$$\frac{\partial F}{\partial B} = (C - 2DB)\left(2 - \frac{B}{L}\right) + (W_o + CB - DB^2)\left(-\frac{1}{L}\right) = 0$$

Solving this equation for B:

$$B = \left(\frac{2}{3}L + \frac{C}{3D}\right)\left\{1 - \sqrt{1 - \frac{2CL - W_o}{3D\left(\frac{2}{3}L + \frac{C}{3D}\right)^2}}\right\}$$

The following equation is the solution for $U^*(L)$:

$$U^*(L) = (W_o + CB - DB^2)\left(2 - \frac{B}{L}\right)$$

when B must be substituted by the previous expression.

Figure 8. Relationship between W(B) line and U*(L) function for simply supported beams.

uniformly distributed over the bridge span. The dead load (multiplied by its load factor 1.1) is then subtracted from the total load and the remainder is divided by the overload factor and impact factor, which are defined in the following paragraphs. The resulting value represents the normal operational live load capacity (U) of bridges whose design criterion is the bending moment.

The overload factor is defined as the ratio of the maximum live load to the maximum permissible live load. It is a function of the quality of law enforcement and the probability of the joint occurrence of loads on bridges. For one-lane bridges where the concept of probability of joint occurrence of loads on the bridge does not apply and for absolute law enforcement, the overload factor would be 1.0. The impact factor is the ratio between the dynamic and static load effects on the structure and is a function of many structure and vehicle parameters. The normal operational live load capacity, U, calculated as indicated previously, can then be represented by a point on the load versus length chart in Figure 8. If this point is above the U* = f(L) curve, the bridge possesses sufficient capacity.

Capacities of many recently built bridges have been plotted in this way and were found to be acceptable. These bridges were all designed for H20-S16 standard live load. The earlier bridges, designed for H20 live load, when checked against the bridge formula loads, were found to be overstressed by less than about 30 percent, except the (unwelded) truss bridges for which the maximum possible overstress is about 40 percent. The stresses corresponding to these percentages are lower than the serviceability stress limits quoted above and are therefore acceptable (5). Bridges of a lower live load standard (H15, H10, etc.) amount to about 30 percent of all bridges and correspond to about 10 percent of the bridge roadway area in Ontario, according to a bridge survey carried out in 1966. Most of these bridges are located in areas where the probability of joint occurrence of overloaded vehicles on the bridge in critical positions is extremely small; and mainly for this reason these bridges have successfully withstood the traffic loads presently on our highways. Few of these bridges need to be posted.

Further investigations now under way include bridge testing for load-carrying capacity and data gathering for closer determination of load impact factors and for studying the validity of statistical assumptions on the probability of the joint occurrence of loads on bridges.

VEHICLE LOAD REGULATIONS

It is possible, using the concept of basic axle weights and the bridge formula, to regulate the axle loads, axle spacings, and gross vehicle weights so as to fully protect the bridges and pavements in the highway system while allowing vehicles to carry the highest possible payloads. In practice the basic axle weights and bridge formula would be used to calculate the maximum gross weight of specific vehicles, knowing the number and spacing of axles. In the case of long trains, the various parts of the configuration would be tested to avoid local overloading of axles or axle groups. A 3-S3 type truck train, for instance, has three axle units and, as well as testing the whole vehicle of six axles, it would be necessary to check the first three axles and then the last five for acceptability. Examples of vehicles that have been tested in this way are shown in Figure 9. It should be noted that, although the loads shown are the maxima for the particular axle configurations, it might be possible to increase the gross loads by rearranging the individual axle loads or axle spacings.

To obtain the optimum distribution of load and axle spacing to secure the maximum possible gross vehicle weight involves a trial and error procedure, and if the computations are done by hand the process becomes tedious. In order to facilitate this work, two aids to computation have been developed. One is a worksheet (Appendix A) that uses typical K coefficients to calculate approximate permissible gross weights, and the other is a nomograph that enables an acceptability check of a specific load configuration to be made very quickly by graphical means (Appendix B).

IMPACT ON CURRENT VEHICLES AND EFFECTS ON NEW DESIGNS

The effects of the proposed regulation on specific types of vehicles in current use are shown in the series of examples of Figure 9. In this figure, axle and gross weights of some present designs of single vehicles, combinations, and trains permitted under the existing regulation are compared with axle and gross weight that would be allowed under the proposed regulation. Gains in gross weight of up to 18 kips (Fig. 9j) are achieved. However, where there is a concentration of loads in the center of the train, as in Figure 9m, there is actually a reduction in permissible gross weight.

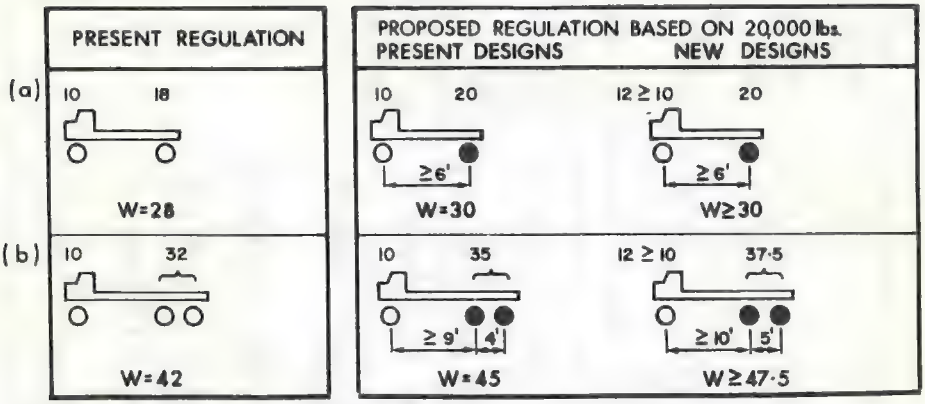
Many vehicles on the roads today are too short for the loads they are carrying and a small percentage would either have to be modified to increase their equivalent base length or their gross weights would have to be reduced to comply with the proposed regulation. An indication of the impact on the vehicles weighed in the 1967 survey is shown in Figures 10 and 11. The numbers in the boxes show the number of vehicles that "plot" in that position on the graph. Those falling above the W/B_m curve would be rejected. In most cases, however, an increase of 2 or 3 ft in the equivalent base length would make them acceptable. A sudden change to the proposed method of regulation would cause unjustifiable hardship to operators of unacceptable vehicles, and, presumably, a reasonable period of exemption would have to be allowed so that they could replace or modify unsuitable vehicles.

As far as the future is concerned, vehicle designers would have much more freedom to optimize designs and, for a given number of axles, gross weights could be much higher than those currently allowed. Acceptable vehicle weight increases with the equivalent base length and an increase in the equivalent base length can be achieved by placing the bulk of the gross weight away from the center of gravity of the vehicle in a symmetrical fashion (both front and rear). This redistribution of the payload would also result in improved riding characteristics of the vehicle and in a decrease of dynamic overload imposed by the vehicle on highway structures. Because the new regulation does not impose a limit on steering axles (unlike the existing restrictions), this rearrangement becomes possible, generating an improved approach to truck design.

ENFORCEMENT AND FEE STRUCTURE

The increase in permissible weights of vehicles is predicated on the assumption that the present load regime does not move upward when the increase becomes effective. This can only be ensured if enforcement measures are introduced that hold the load regime to present levels. The introduction of axle weight control will aid immeasurably

SINGLE VEHICLES



VEHICLE — SEMITRAILER COMBINATIONS

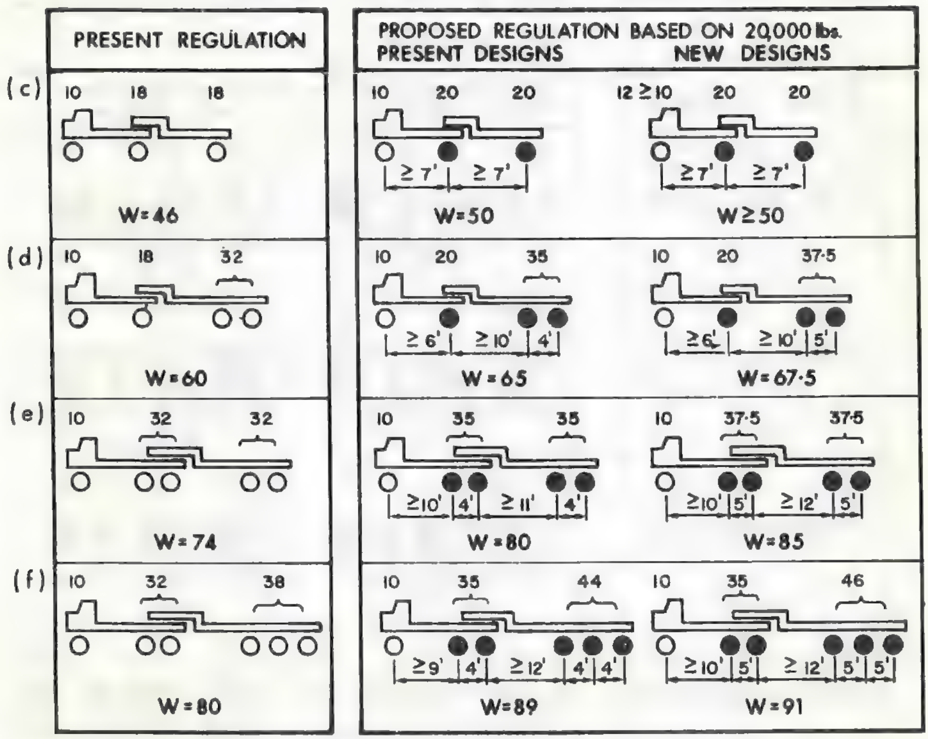
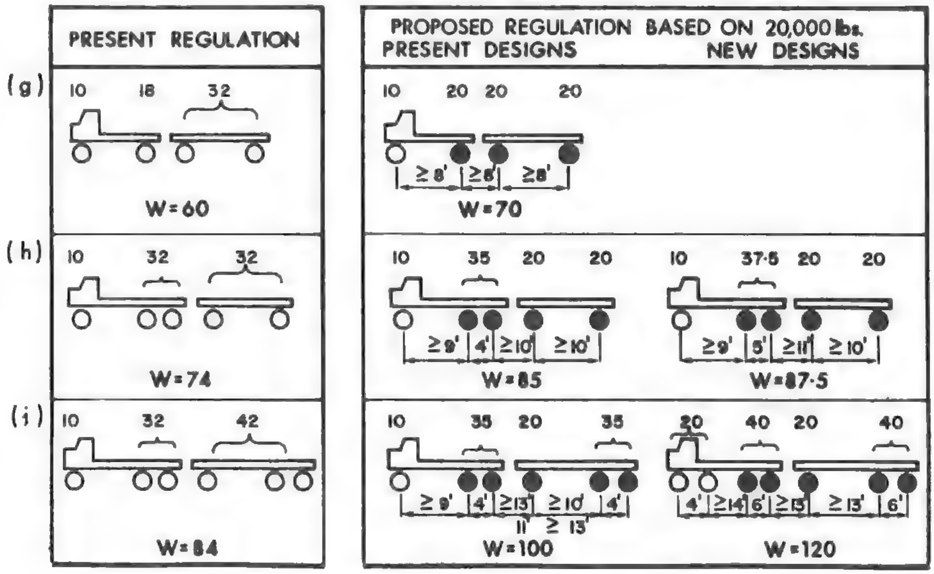


Figure 9. Actual and possible vehicle designs (in kips).

VEHICLE – TRAILER COMBINATIONS



VEHICLE TRAINS

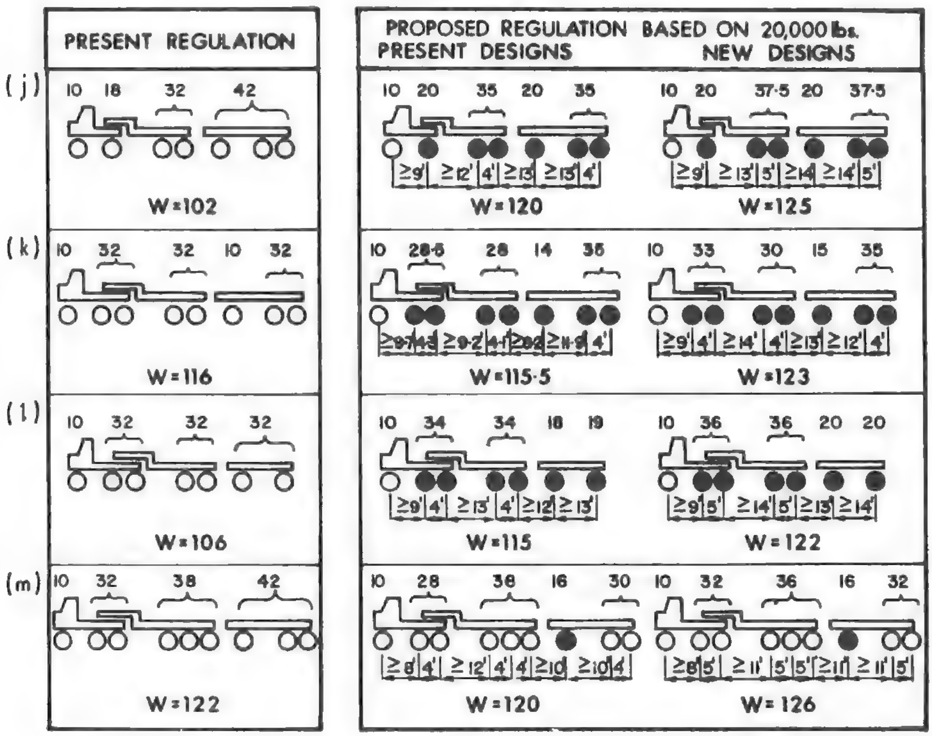


Figure 9. (Continued).

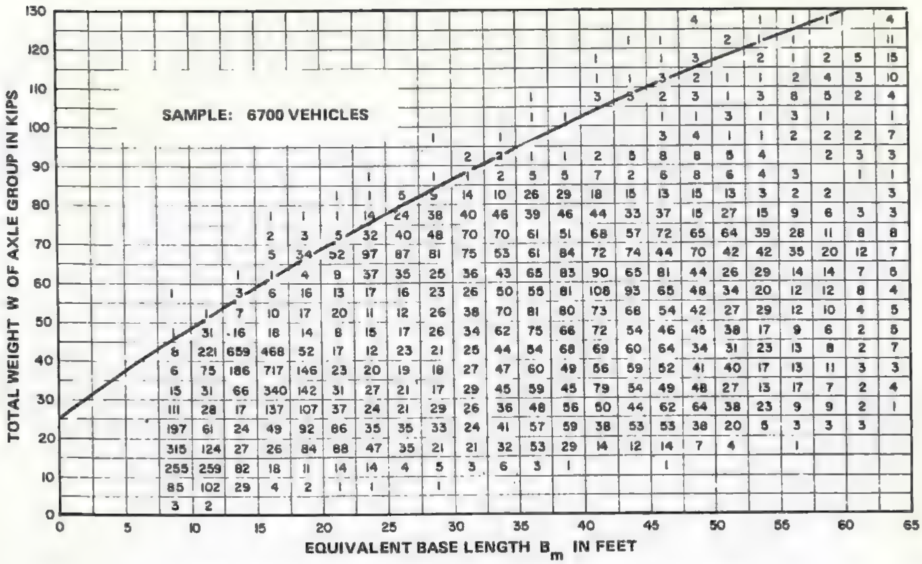


Figure 10. Acceptance diagram for all vehicles in 1967 survey.

in this effort but the results of any set of enforcement measures can only be appraised by periodic surveys of axle weights, and enforcement procedures should provide for such surveys to be made independent of the regular enforcement checks.

In conjunction with the introduction of load regulation based on the principles outlined in this paper, it would be possible (although this is not presently envisaged) to introduce a license fee structure in which the fee would be based on the damaging power of the vehicle. Using Figure 5, each vehicle can be assigned a load factor based on the number of axles and the loads it will carry. Each axle unit would be converted into an equiv-

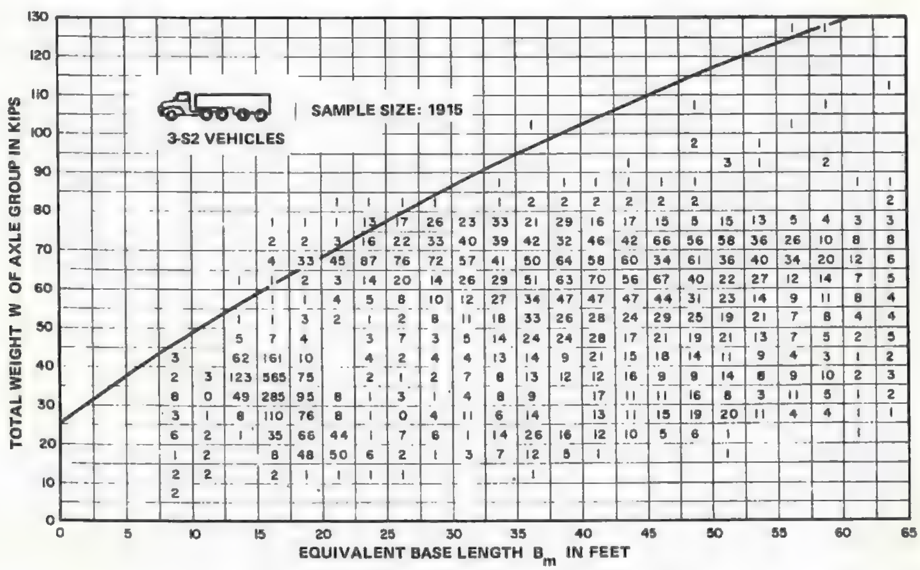


Figure 11. Acceptance diagram for 3-S2 vehicles.

alent number of 20-kip single axles and the sum of these numbers would be the vehicle load factor. This method is illustrated below for a 3-S3-2 train:

10-kip steering axle	0.1	20-kip single axle load
30-kip dual axle of the tractor	0.5	
40-kip triple axle of the semitrailer	0.4	
17-kip steering axle of the trailer	0.4	
17-kip rear axle of the trailer	0.4	
Total equivalency factor	1.8	vehicle load factor

Such a vehicle would then be charged a license fee of 1.8 times the basic fee.

CONCLUDING REMARKS

The proposed regulations (legislation based on these proposals becomes effective in Ontario March 1, 1971) envisage control of axle weights as well as gross weights and also take account of axle spacings. The permissible axle and gross weights are determined from the axle configuration and vary upward or downward depending on the degree of load concentration.

These proposals would permit increases in permissible gross weights for most existing vehicles. Gains in permissible gross weight for long trains are relatively small and there are some trains with short-wheelbase units for which special provisions have to be made until they can be either modified or replaced. Opportunity exists in the design of new vehicles to take advantage of the regulations to increase the gross weight gains even further. More rigorous enforcement procedures must be introduced to ensure that the spectrum of loads now on the roads does not shift upward, and the effectiveness of these enforcement procedures must be periodically evaluated by carrying out vehicle surveys.

The advantages to be gained by introducing the proposed method are that existing bridges and pavements would be protected, most existing vehicles would be able to carry larger payloads, and new vehicles could be designed for even higher gross loads.

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4. Tamberg, K. G., Csagoly, P. F., and Jung, F. W. Application of Transformed Highway Loads to Influence Lines of Any Shape. Department of Highways, Ontario, Rept. No. RR131, 1967.
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Appendix A

INSTRUCTIONS IN THE USE OF THE VEHICLE LOADING WORKSHEET

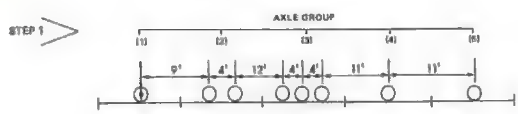
The following procedure should be followed to determine the optimum permissible axle weights of a vehicle configuration. A 3-S3-2 vehicle is used as an example to assist the reader. In actual practice, the axle configuration of the truck in question should be

used. After a few applications of the worksheet, the reader will be able to dispense with these instructions and complete the worksheet with only brief reference to the steps of the procedure.

Step 1. Write in the space provided the axle configuration of the truck or vehicle train, and enter the interaxle distances to the nearest ¼ ft as shown in Figure 12.
Step 2. Enter the basic axle weight for each group of axles as determined from Table 1. Add these basic weights to determine the gross weight.
Step 3. Enter (under b, in the lower part of the worksheet) the distance between the outer axles of each of the possible axle configurations. In the example for axle configuration (1) (2), b is 9 + 4 = 13 ft. Similarly, for configuration (1) (2) (3), b is 9 + 4 + 12 + 4 + 4 = 33 ft. Complete the column for all possible axle configurations.
Step 4. Enter (under B_m) the product of k $\times$ b. In the example for axle configuration (1) (2), B_m is 1.1 $\times$ 13 = 14.3. Similarly, for axle configuration (1) (2) (3), B_m is 1.1 $\times$ 33 = 36.3. Complete the column for all possible axle configurations.
Step 5. Enter (under W_m) the corresponding values of W_m determined from Table 2. In the example for configuration (1) (2), W_m for a B_m of 14.3 = 48.0. Similarly, for configuration (1) (2) (3), W_m for a B_m of 36.3 = 85.5. Complete the column for all possible axle configurations.
Step 6. Enter (under P,) the sum of the basic weights for each axle configuration (values entered in Step 2). In the example for axle configuration (1) (2), P is 10 + 35 = 45 kips. Similarly, for axle configuration (1) (2) (3), P is 10 + 35 + 44 = 89 kips. Complete the column for all possible axle configurations.
Step 7. To determine the acceptability of the load on each axle group, the P values must now be compared with their respective W_m values. If any P value is larger than its corresponding W_m value, it is unacceptable, and the weights on the axle groups must be adjusted downward (refer to Step 8) to achieve an acceptable P value.

VEHICLE LOADING WORKSHEET

(a)



(b)

		AXLE WEIGHTS* P					GROSS* WEIGHT W
		(1)	(2)	(3)	(4)	(5)	
STEP 2	BASIC (Table 1)	10	35	44	20	20	129
STEP 8 & 9	1ST TRIAL	10	30	38	14.5	20	112.5
STEP 11	2ND TRIAL						

(c)

	STEP 3	STEP 4	STEP 5	STEP 6	STEP 10	STEP 12
AXLE CONFIGURATION	k x b	= B_m	W_m (Determine from Table 2)	SUM OF BASIC P	SUM OF 1ST TRIAL P	SUM OF 2ND TRIAL P
(1)(2)	1.1 x 13	= 14.3	48.0	45	40	
(1)(2)(3)	1.1 x 33	= 36.3	85.5	89	78	
(1)(2)(3)(4)	1.1 x 44	= 48.4	103.5	109	92.5	
(1)(2)(3)(4)(5)	1.0 x 55	= 55	112.5	129	112.5	
(2)(3)	1.3 x 24	= 31.2	78.0	79	68	
(2)(3)(4)	1.1 x 35	= 38.5	89.0	99	82.5	
(2)(3)(4)(5)	1.1 x 46	= 50.6	106.5	119	102.5	
(3)(4)	1.3 x 19	= 24.7	67.0	64	52.5	
(3)(4)(5)	1.2 x 30	= 36.0	85.5	84	72.5	
(4)(5)	1.3 x 11	= 14.3	48.0	40	34.5	

* Weights in kips (units of 1000 lbs.)

Figure 12. Example of a completed worksheet.

TABLE 1
BASIC WEIGHTS ON AXLE UNITS

SINGLE-AXLE

SPACING IN FEET	GROSS WEIGHT IN KIPS
—	—
—	**20.0**

DUAL-AXLE

SPACING IN FEET	GROSS WEIGHT IN KIPS
< 4.0	32.0
4.0	**35.0**
4.25	35.5
4.5	36.0
4.75	36.5
5.0	37.5
5.25	38.0
5.5	38.5
5.75	39.0
6.0	40.0

TRIPLE-AXLE

SPACING IN FEET	GROSS WEIGHT IN KIPS
< 8.0	40.0
8.0	**44.0**
9.0	44.0
9.25	44.5
9.5	45.0
9.75	45.5
10.0	46.0
10.25	46.5
10.5	47.5
10.75	48.0
11.0	49.0
11.25	49.5
11.5	50.0
11.75	50.5
12.0	51.0
12.25	51.5
12.5	52.5
12.75	53.0
13.0	54.0
13.25	54.5
13.5	55.0
13.75	55.5
14.0	56.0
14.25	56.5
14.5	57.0
14.75	57.5
15.0	58.5
15.25	59.0
15.5	59.5
15.75	59.5
16.0	60.0

NOTES:

1. *Maximum weight per inch of tire width ⩽ 600 lb.*
2. *Front steering axle with single tires is usually 10 kips.*
3. *Most commonly occurring axle spacings and basic weights are heavily framed in the table.*

TABLE 2
MAXIMUM PERMISSIBLE WEIGHT, W_m, ON ANY AXLE GROUP IN A CONFIGURATION OF A HEAVY VEHICLE

B_m feet	0	10	20	30	40	50	60	70
0.00		40.0	58.5	75.5	91.5	106.0	118.5	130.0
0.25		40.5	59.0	76.0	92.0	106.0	119.0	130.5
0.50		41.0	59.5	76.5	92.0	106.5	119.0	130.5
0.75		41.5	60.0	77.0	92.5	107.0	119.5	131.0
1.00		42.0	60.5	77.5	93.0	107.0	120.0	131.0
1.25		42.5	61.0	78.0	93.5	107.5	120.0	131.5
1.50		43.0	61.0	78.0	93.5	108.0	120.5	131.5
1.75		43.5	61.5	78.5	94.0	108.0	120.5	132.0
2.00		44.0	62.0	79.0	94.5	108.5	121.0	132.0
2.25		44.5	62.5	79.5	95.0	109.0	121.5	132.5
2.50		45.0	63.0	80.0	95.0	109.0	121.5	133.0
2.75		45.0	63.5	80.0	95.5	109.5	122.0	133.0
3.00		45.5	64.0	80.5	96.0	109.5	122.0	133.5
3.25		46.0	64.5	81.0	96.0	110.0	122.5	133.5
3.50		46.5	64.5	81.5	96.5	110.5	123.0	134.0
3.75		47.0	65.0	82.0	97.0	111.0	123.0	134.0
4.00	28.0	47.5	65.5	82.0	97.5	111.0	123.5	134.5
4.25	28.5	48.0	66.0	82.5	97.5	111.5	123.5	134.5
4.50	29.0	48.5	66.5	83.0	98.0	111.5	124.0	135.0
4.75	29.5	49.0	67.0	83.5	98.5	112.0	124.5	135.0
5.00	30.0	49.5	67.5	84.0	99.0	112.5	124.5	135.5
5.25	30.5	50.0	67.5	84.0	99.0	112.5	125.0	
5.50	31.0	50.5	68.0	84.5	99.5	113.0	125.0	
5.75	31.5	51.0	68.5	85.0	100.0	113.5	125.5	
6.00	32.0	51.5	69.0	85.5	100.0	113.5	125.5	
6.25	32.5	52.0	69.5	85.5	100.5	114.0	126.0	
6.50	33.0	52.0	70.0	86.0	101.0	114.0	126.5	
6.75	33.5	52.5	70.5	86.5	101.5	114.5	126.5	
7.00	34.0	53.0	70.5	87.0	101.5	115.0	127.0	
7.25	34.5	53.5	71.0	87.5	102.0	115.0	127.0	
7.50	35.0	54.0	71.5	87.5	102.5	115.5	127.5	
7.75	35.5	54.5	72.0	88.0	102.5	116.0	127.5	
8.00	36.0	55.0	72.5	88.5	103.0	116.0	128.0	
8.25	36.5	55.5	73.0	89.0	103.5	116.5	128.0	
8.50	37.0	56.0	73.0	89.0	103.5	117.0	128.5	
8.75	37.5	56.5	73.5	89.5	104.0	117.0	129.0	
9.00	38.0	57.0	74.0	90.0	104.5	117.5	129.0	
9.25	38.5	57.0	74.5	90.5	104.5	117.5	129.5	
9.50	39.0	57.5	75.0	90.5	105.0	118.0	129.5	
9.75	39.5	58.0	75.5	91.0	105.5	118.5	130.0	

Note: Axle weights shown in kips (1,000 lb.)

Table values are based on equation: $W_m = 20 + 2.07\,B_m - 0.0071\,B_m^2$

Step 8. The total W_m for the complete vehicle is the maximum gross weight W that is permitted for the vehicle. In the example configuration (1) (2) (3) (4) (5) is the complete vehicle and the W_m is 112.5 kips. This must now be entered on the worksheet as the new gross weight W for the vehicle.

Step 9. Enter along the 1st Trial line adjusted weights for the axle configurations so that, when added, their total weight does not exceed the new gross weight. In the example this is 112.5 kips.

Step 10. Repeat Step 6 using the adjusted weights and compare the P values obtained with their corresponding W_m values. Again no P value must exceed its corresponding W_m value.

Step 11. Repeat Steps 9 and 10 if necessary until the P values of the adjusted weights are not more than their corresponding W_m values and the total weights of the axle configuration do not exceed the new gross weight W. The weights thus entered in the final trial line will be the highest permissible weights that can be derived by this procedure. (The ultimate maximum permissible weights can be determined by substituting accurate values of K for the fixed values shown in the worksheet.)

CALCULATION OF ACCURATE K VALUES

In determining the maximum permissible weight (W_m) of an axle configuration (Step 5, Fig. 12), the corresponding B_m value (Step 4, Fig. 12) is calculated by multiplying the b value of each axle configuration (Step 3, Fig. 12) by a predetermined value of K. These values of K result in conservative estimates of permissible weights. To obtain higher permissible weights for axle configurations it is necessary to substitute accurately calculated values of K for those listed in the worksheet in accordance with the following procedure.

Figure 13 is representative of a general axle configuration, and point m is chosen as the axle nearest to the center of gravity of the loads.

Accurate values of K are calculated for any configuration of axles from the formula

$$K = \frac{4(M_R + M_L)}{Wb} - \frac{2(N-1)}{N}\left(\frac{c}{b}\right)^2 \tag{1}$$

where

$M_R = \sum_{m}^{N} P_i x_i$ and is the sum of the moments of the loads to the right of m taken about m (kip-ft, to be taken as positive);

$M_L = \sum_{i=1}^{m} P_i x_i$ and is the sum of the moments of the loads to the left of m taken about m (kip-ft, to be taken as positive);

$W = \sum_{i=1}^{N} P_i$ and is the sum of the loads on the complete axle configuration;

N = the number of axles in the configuration;

b = the distance in feet between the extreme outer axles of the configuration; and

$c = \frac{M_R - M_L}{W}$ and is the distance in feet of the center of gravity from point m.

There are two noteworthy points that will aid in using the above equation, as follows:

1. The quantity c is usually quite small and where the ratio $\frac{c}{b}$ is smaller than 0.05, the last term in the equation can be neglected. Thus

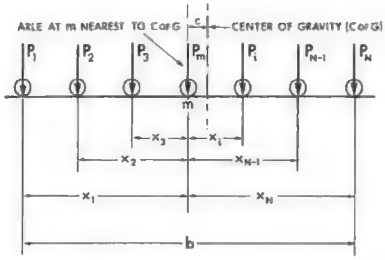


Figure 13. General axle configuration.

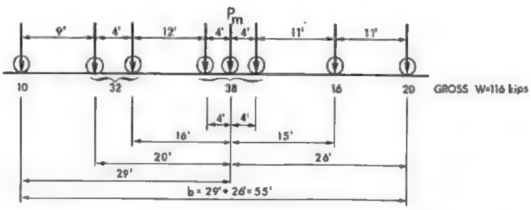


Figure 14. Axle weight configuration of 2nd Trial.

$$K \cong \frac{4(M_R + M_L)}{Wb} \tag{2}$$

Equation 2 can therefore be used to obtain approximate K values that are quite close to accurately calculated K values (within ½ percent).

2. Because b is a constant for each axle configuration, in Eq. 2, the value of K for that configuration can be optimized by obtaining the largest values for M_R and M_L, i.e., by placing the heaviest loads toward the extremities of the configuration.

To illustrate the benefits of applying accurate K values to the worksheet calculations, the 3-S3-2 vehicle in Figure 12 is used as an example. For this example the new gross weight of the complete vehicle configurations (1), (2), (3), (4), and (5) has been calculated by application of the worksheet as 112.5 kips rather than the original basic gross weight estimation of 129 kips.

The next step in the procedure is to observe the differences between the W_m values and corresponding P values of the other axle configurations (Steps 5 and 10, Fig. 12) and to select the configuration of axles that has a sum of P value closest to its corresponding W_m value. In this example for configuration (2) (3) (4) (5), W_m = 106.5 and the sum of P = 102.5 kips.

If a steering axle of 10 kips is added to axle configuration (2) (3) (4) (5), such a vehicle would have a permissible weight of 10 + 106.5 = 116.5 kips. From this it appears feasible that a gross vehicle weight of at least 116 kips is possible instead of the previously calculated 112.5 kips. Thus 116 kips should be entered as the new gross weight at the end of the 2nd Trial line on the worksheet. For convenience in calculating accurate K values, the axle configuration is re-drawn in Figure 14.

The accurate K value for configuration (1) (2) (3) (4) (5) is calculated as follows:

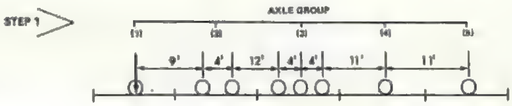
$$\begin{aligned}
W &= \text{sum of weights on each axle} \\
&= 10 + 32 + 38 + 16 + 20 = 116 \text{ kips;} \\
M_L &= \text{sum of moments due to loads to the left of m} \\
&= (10 \times 29) + \left(\frac{32}{2} \times 20\right) + \left(\frac{32}{2} \times 16\right) + \left(\frac{38}{3} \times 4\right) \\
&= 916\tfrac{2}{3} \text{ kip-ft;} \\
M_R &= \text{sum of moments due to loads to the right of m} \\
&= \left(\frac{38}{3} \times 4\right) + (16 \times 15) + (20 \times 26) \\
&= 810\tfrac{2}{3} \text{ kip-ft;} \\
M_L + M_R &= 1{,}727\tfrac{1}{3} \text{ kip-ft;} \\
M_R - M_L &= -106 \text{ kip-ft; and} \\
\frac{c}{b} &= \frac{M_R - M_L}{Wb} = \frac{-106}{116 \times 55} = 0.0166 < 0.05.
\end{aligned}$$

Therefore, neglecting the last term in Eq. 1:

$$\begin{aligned}
K &= \frac{4(M_L + M_R)}{Wb} = \frac{4 \times 1{,}727\tfrac{1}{3}}{116 \times 55} \\
&= 1.084
\end{aligned}$$

VEHICLE LOADING WORKSHEET

(a)



(b)

	AXLE WEIGHTS* P					GROSS* WEIGHT W
	(1)	(2)	(3)	(4)	(5)	
STEP 2 BASIC (Table 1)	10	35	44	20	20	129
STEP 8 & 9 1ST TRIAL	10	30	38	14.5	20	112.5
STEP 11 2ND TRIAL	10	32	38	16	20	116

(c)

AXLE CONFIGURATION	k x b = B_m (STEP 3, STEP 4)	W_m (Determine from Table 2) (STEP 5)	SUM OF BASIC P (STEP 6)	SUM OF 1ST TRIAL P (STEP 10)	SUM OF 2ND TRIAL P (STEP 12)
(1)(2)	1.1 x 13 = 14.3	48.0	45	40	42
(1)(2)(3)	1.1 x 33 = 36.3	85.5	89	78	80
(1)(2)(3)(4)	1.1 x 44 = 48.4	103.5	109	92.5	96
(1)(2)(3)(4)(5) **	1.084 ~~1.0~~ x 55 = 59.6 ~~55~~	118.0 ~~112.5~~	129	112.5	116
(2)(3)	1.3 x 24 = 31.2	78.0	79	68	70
(2)(3)(4)	1.1 x 35 = 38.5	89.0	99	82.5	86
(2)(3)(4)(5)	1.1 x 46 = 50.6	106.5	119	102.5	106
(3)(4)	1.3 x 19 = 24.7	67.0	64	52.5	54
(3)(4)(5)	1.2 x 30 = 36.0	85.5	84	72.5	74
(4)(5)	1.3 x 11 = 14.3	48.0	40	34.5	36

* *Weights in kips (units of 1000 lbs.)*

** *Changes indicate benefits from substitution of accurate K-values*

Figure 15. Example illustrating the benefit of substituting accurately calculated K values.

Substitute this value of K in the worksheet for axle configuration (1) (2) (3) (4) (5) as shown in Figure 15 and obtain a different value for B_m (59.6) and a higher value for W_m (118.0 kips). Complete Step 12 of Figure 15 by obtaining sums of P for the various axle configurations. It will now be seen that the second trial weights are acceptable. In some cases the process of calculating accurate K values for other configurations will result in higher permissible weights but, as the number of axle configurations with sum of P values closest to their corresponding W_m values taken as critical increase, the yield in increased permissible gross weight may not be large enough to compensate for the time and efforts needed for the calculations.

Appendix B

ALTERNATIVE METHOD OF DETERMINING APPROXIMATE PERMISSIBLE WEIGHTS

This nomograph and step procedure presents an alternative method for determining a first estimate of permissible axle loads and gross vehicle loads.

Step 1. Assuming an axle configuration similar to that shown in Figure 16, select P_5 as the axle nearest to the center of gravity of the truck train and designate it P_m.

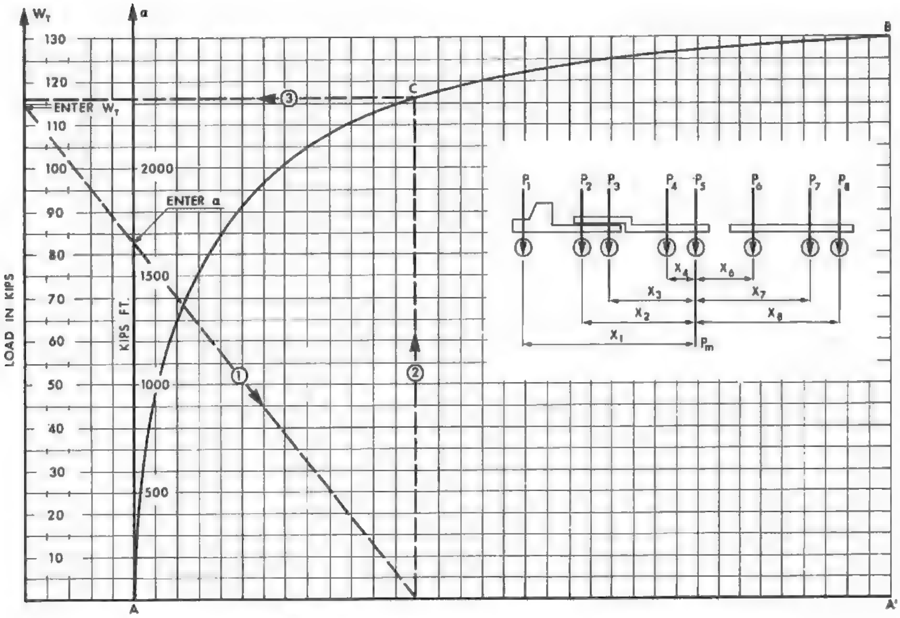


Figure 16. Nomograph for determining approximate total weights.

Step 2. Calculate the distance x (in feet) that each axle is from P_m.

Step 3. Assign tentative load values P (in kips) to each axle (use Table 1 in Appendix A as a guide).

Step 4. Determine a as follows:

$$a = P_1x_1 + P_2x_2 + P_3x_3 + P_4x_4 + P_5x_5 + P_6x_6 + P_7x_7 + P_8x_8$$

Step 5. Determine W_T as follows:

$$W_T = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8$$

Step 6. Enter a and W_T on the nomograph (Fig. 16) and draw a straight line (accurately) from W_T through a to intersect line AA′.

Step 7. Draw a straight vertical line (accurately) from this point to intersect curved line AB. Designate this point C.

Step 8. Draw a horizontal line (accurately) from point C to intersect the load scale W. If this line intersects the load scale above the point of entry of W_T (refer to Step 6), the gross load for the vehicle is tentatively suitable and the final check by calculation of accurate K values (Eq. 1, Appendix A) can be made. If the intersection of the load scale is below the point of entry of W_T, the gross load of the vehicle is unacceptable. If this is the case, change the assigned values of P for each axle and repeat steps until an acceptable tentative gross load is obtained.

Note: Larger acceptable loads may possibly be accommodated by placing load concentrations toward the ends of the truck-train configurations. Load concentration near P_m will not produce optimum gross loads.

Where the distance between P_m and the center of gravity of the truck is large, the estimated gross load is likely to be too high.

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